PB84-194851

Radionuclide Removal for Small Public Water Systems

SMC Martin, Inc., Valley Forge, PA

Prepared for

Environmental Protection Agency, Washington, DC

Jun 83

U.S. Department of Commerce
National Technical Information Service
NTIS

United States
Environmental Protection
Agency

Office of
Drinking Water (WH-550)
Washington, DC 20460

EPA 570/9-83-010
June 1983

PB84-194851

EPA

Radionuclide Removal for Small Public Water Systems

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA 570/9-83-010

2.

3. RECIPIENT'S ACCESSION NO. PB84 194851

4. TITLE AND SUBTITLE
Radionuclide Removal for Small Public
Water Systems

5. REPORT DATE June 1983

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S) SMC Martin Inc.

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
SMC Martin Inc.
900 West Valley Forge Road
Valley Forge, PA 19482

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO. 68-01-6285

12. SPONSORING AGENCY NAME AND ADDRESS
U.S. Environmental Protection Agency
Office of Drinking Water (WH-550)
401 M Street SW
Washington, D.C. 20460

13. TYPE OF REPORT AND PERIOD COVERED Technical

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

This document has been prepared to aid water utility owners, engineers, operators and municipal managers in understanding and dealing with excessive radionuclide levels in their water supply. It is intended to be used for defining the problem, developing or evaluating proposed solutions, and explaining to water consumers why radionuclides are controlled and what the approximate cost of control will be. This handbook is designed as a technical guide to radionuclide removal for those smaller size systems that have decided that radionuclide control is desirable. This document contains no regulatory policy and does not obligate systems to use any treatment or nontreatment technique to reduce radionuclide concentrations.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
radionuclides drinking water public water systems small water systems		

18. DISTRIBUTION STATEMENT Open

19. SECURITY CLASS (This Report) Non-Sensitive

20. SECURITY CLASS (This page)

21. NO. OF PAGES 162

22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

RADIONUCLIDE REMOVAL
FOR
SMALL PUBLIC WATER SYSTEMS

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Contract No. 68-01-6285

June 1983

ACKNOWLEDGEMENT

This manual was prepared for U.S. Environmental Protection Agency under Contract No. 68-01-6285. Mr. Chester Pauls, EPA Project Officer, provided valuable guidance to the project. The manual was compiled by SMC Martin Inc. in cooperation with the following:

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I. SUMMARY AND OVERVIEW

PURPOSE

This document has been prepared to aid water utility owners, engineers, operators and municipal managers in understanding and dealing with excessive radionuclide levels in their water supply. It is intended to be used for defining the problem, developing or evaluating proposed solutions, and explaining to water consumers why radionuclides are controlled and what the approximate cost of control will be. Although the handbook may be useful to larger utilities, it is intended primarily to support the water quality improvement efforts of smaller utilities that may lack the technical and financial resources of larger systems.

This handbook is designed as a technical guide to radionuclide removal for those smaller size systems that have decided that radionuclide control is desirable. This document contains no regulatory policy and does not obligate systems to use any treatment or nontreatment technique to reduce radionuclide concentrations. If appropriate, those regulatory requirements are or will be established by the primacy agency as part of its implementation of the Primary Drinking Water Regulations.

The handbook is divided into eight sections, plus references, as follows:

Section	Subject Guide
I	Summary and Overview
II	Introduction - Discusses the structure of matter, the units of radioactivity, radionuclides in drinking water, health effects, federal regulations, and the monitoring and analysis requirements for detecting radionuclides in water.
III	Nontreatment and Treatment Alternatives - Different approaches to solving excess radionuclide problems.
IV	Design of Radionuclide Removal Systems - Describes and compares lime-soda softening, ion-exchange, and reverse osmosis treatment systems. Examples of design calculations and lists of suppliers are presented.
V	Waste Residue Handling - Discusses disposal methods for waste by-products generated by different radionuclide removal systems.
VI	Cost Estimating Procedures and Funding Sources - Capital capacity, sources of loans, grants and other financial assistance are discussed. The methods used to determine costs are explained and an example is presented to demonstrate the use of the method.
VII	Operation and Maintenance - Presents basic guidelines for operating radionuclide removal systems, including water quality monitoring and equipment maintenance.

VIII Case Histories - Discusses the experience of three utilities which are treating the water supply to remove excess radionuclides.

WHAT ARE RADIONUCLIDES

Radionuclides are chemical elements which undergo spontaneous nuclear decay, thereby emitting various forms of radiation energy. Radionuclides may originate from both natural and man-made sources.

Radium is the naturally occurring radionuclide of most concern in the U. S. Radium is leached under natural conditions into ground waters from radium-bearing deposits found in rock strata and phosphate rock. Uranium, another natural radionuclide, may also leach into ground waters under natural conditions. Both uranium and radium, may also enter surface water supplies from man's activities such as from stormwater runoff from the tailings of mining operations and discharges from medical and industrial activities. Man-made radionuclides may also contaminate water supplies as a result of fallout from nuclear weapons detonation or accidental discharge from nuclear power facilities. Excessive levels of man-made radionuclides in drinking water are anticipated only in transient situations following a major contaminating event.

RADIONUCLIDE HEALTH EFFECTS

Radioactivity has been known for many years to produce detrimental biological effects to humans, including developmental abnormalities, cancer, and death. The primary basis for the United States Environmental Protection Agency (EPA) radionuclide regulations for drinking water is the carcinogenic potential of this material. Although currently there appears to be no completely safe lower limit of exposure to any radionuclide, human ingestion of potable water which contains radionuclides at levels below the maximum contaminant levels (MCLs) allowed by the National Interim Primary Drinking Water Regulations (NIPDWR, see Reference 2) results in minimal health risk.

ALTERNATIVE METHODS TO REDUCE EXCESSIVE RADIONUCLIDES IN DRINKING WATER

If radionuclides in the drinking water supply are excessive, steps should be taken to reduce these levels. Figure 1-1 depicts alternatives available to a utility for radionuclide removal.

As discussed in this document, radionuclide removal can involve significant costs. Before buying a treatment system for radionuclide removal, the utility should carefully study all nontreatment approaches as discussed in Section III of this document. It may also be possible to blend a water with excessive radionuclides with one having little radionuclide contamination, to produce a blended water of acceptable quality.

There are four practical and available methods for reducing excessive concentrations of radionuclides in drinking water:

1. Blending with a water from an alternative source having less contamination.

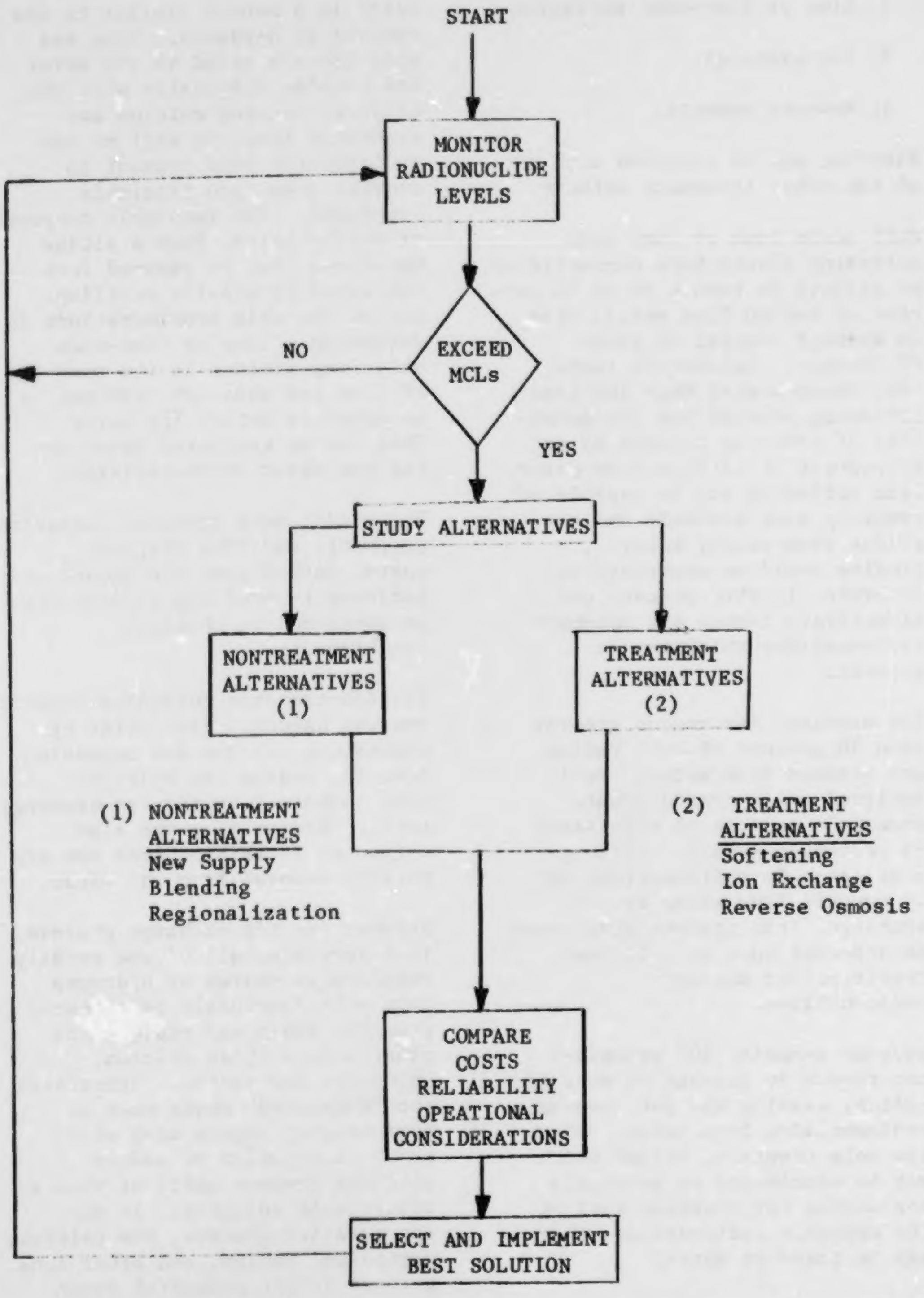
START
MONITOR RADIONUCLIDE LEVELS
EXCEED MCLs
NO
YES
STUDY ALTERNATIVES
NONTREATMENT ALTERNATIVES (1)
TREATMENT ALTERNATIVES (2)
(1) NONTREATMENT ALTERNATIVES
New Supply
Blending
Regionalization
(2) TREATMENT ALTERNATIVES
Softening
Ion Exchange
Reverse Osmosis
COMPARE COSTS RELIABILITY OPEATIONAL CONSIDERATIONS
SELECT AND IMPLEMENT BEST SOLUTION

Figure 1-1. Alternative Methods for Reducing Excessive Radionuclide Concentrations in Drinking Water

2. Lime or lime-soda softening.

3. Ion exchange.

4. Reverse osmosis.

Blending may be combined with any of the other treatment methods.

Full scale lime or lime-soda softening plants have demonstrated an ability to remove 60 to 94 percent of radium from water, with an average removal of about 80 percent. Laboratory tests have demonstrated that the lime softening process has the potential of removing between 85 and 98 percent of uranium from water. Lime softening may be capable of removing some man-made radionuclides from water; however, studies would be necessary to determine if this process can effectively remove any man-made radionuclides which may be present.

Ion exchange can remove greater than 90 percent of both radium and uranium from water. Well designed and operated plants should be capable of consistent 95 percent removals. Although some man-made radionuclides may be removed from water by ion exchange, this process should not be depended upon as a blanket treatment for man-made radionuclides.

Reverse osmosis (RO) processes can remove 90 percent or more of radium, uranium and most man-made radionuclides from water. RO is the only treatment method which may be considered as generally applicable for treating most of the man-made radionuclides that may be found in water.

The lime and lime-soda softening processes remove radium from water in a manner similar to the removal of hardness. Lime and soda ash are added to the water and combine chemically with the hardness causing calcium and magnesium ions, as well as any radionuclide ions present to convert them into insoluble compounds. The insoluble compounds, or precipitates, form a sludge which can then be removed from the water by gravity settling. One of the main considerations in designing a lime or lime-soda softening process is the quantity of lime and soda ash required to be added to soften the water. This can be estimated based on the raw water characteristics.

The sludge mass produced requiring disposal, and thus disposal costs, depend upon the amount of hardness removed and is directly proportional to chemical requirements.

The ion-exchange softening process removes hardness from water by exchanging calcium and magnesium ions for sodium (or hydrogen) ions contained in the ion-exchange resin. Radium ions are also exchanged in this process and are thereby removed from the water.

Because the ion-exchange process is reversible, all of the readily replaceable sodium or hydrogen ions will eventually be released from the resin and replaced by other ions such as calcium, magnesium and radium. Therefore, the "exhausted" resin must be periodically regenerated with brine, a solution of sodium chloride (common salt) or with a dilute acid solution. In the regeneration process, the calcium, magnesium, radium, and other ions present in the exhausted resin are replaced with a fresh supply of sodium or hydrogen ions from the regenerating solution. Then, after washing the resin with water to free it from brine or acid, the regenerated exchange resin is ready to soften an additional supply of water.

Resins may also be used to remove uranium from waters. However, because uranium is present predominantly in the anionic (negatively charged) ion form, anionic exchange resins are required. A mixture of sodium chloride and sodium bicarbonate are used for regeneration of the anionic exchange resin.

The exchange capacity of the ion-exchange resin and the quantity of salt required for resin regeneration are primary considerations in designing an ion-exchange treatment system. This information can be obtained from the ion-exchange resin manufacturer once the raw water characteristics are known. Regenerant brine and resin washwater streams are contaminated with dissolved solids and require disposal in an environmentally acceptable manner.

Reverse osmosis is a process in which water is forced through a semipermeable membrane that will not pass dissolved substances.

Thus, calcium, magnesium, radionuclides, and other ions in solution will be removed from the product water as it passes through the membrane. The main design consideration for a reverse osmosis system is the pumping pressure required to force the water through the membrane. The pumping pressure is directly dependent on the concentration of dissolved solids in the raw water. Manufacturers of reverse osmosis systems can supply much of the required design information once the raw water characteristics, including dissolved solids, are known. The reject stream from a reverse osmosis plant contains high levels of dissolved solids and requires special disposal considerations.

Because the treated water following ion-exchange or reverse osmosis treatment is normally much lower in radionuclide content than required by the standards, it may be blended with the raw water to produce a finished water of acceptable quality. Blending of treated and raw water is more economical than treating all of the raw water because the treatment facilities are designed based on the volume of water treated. The portion of raw water to be treated so that the blended water radionuclide level is acceptable is dependent upon the raw water radionuclide concentration and the performance of the treatment system with respect to both radionuclides and other (conventional) regulated parameters.

DESIGNING A RADIONUCLIDE REMOVAL SYSTEM

Design of a radionuclide removal system involves these main considerations:

1. Characteristics of the raw water.
2. Required radionuclide reduction to achieve an acceptable water quality and to comply with primary drinking water regulations.
3. Quantity of water to be treated.

Lime or lime-soda softening is most applicable to waters of moderate to high total hardness (about 120 to 400 mg/l of total hardness [TH] as $CaCO_3$) where the total dissolved solids are about 750 mg/l or less. When the raw water source is harder than about 400 mg/l, large chemical requirements often render lime or lime-soda softening impractical. Lime softening may not be practical for radionuclide removal from low hardness ($<$ 120 mg/l TH as $CaCO_3$) waters, although site specific data are unavailable on such an application. Bench or pilot scale testing should be conducted to determine the performance and cost effectiveness of lime softening for radionuclide removal from low hardness waters prior to implementing such a system.

Ion exchange for radionuclide removal is applicable to waters of very low to moderate hardness and total dissolved solids (TDS) (about 0 to 400 mg/l of TH as $CaCO_3$ and 500 mg/l or less). Since TDS levels often increase slightly through a typical brine regenerated ion exchange system, the 500 mg/l TDS limitation on ion exchange systems is necessary to prevent a finished water from exceeding the 500 mg/l secondary MCL for TDS.

For the highly mineralized water cases, hydrogen cycle (acid regenerated) ion exchange units could be used which would produce an acceptable water quality for TDS; however, the practical implications of its use for small systems frequently preclude its serious consideration.

Reverse osmosis, although more expensive than the other alternatives, is most applicable to waters above 500 mg/l TDS. RO can be used, however, to remove radionuclides in water of lower mineral content.

Raw water radionuclide content must be considered in selecting a treatment system capable of producing a finished water that meets NIPDWR standards. For instance, lime or lime-soda softening processes should not be considered when the (unblended) raw water radium concentration is greater than 25 picoCuries per liter (pCi/l), since the average radium reduction of 80 percent would not be adequate to meet the radium standard of 5 pCi/l. (Sorg has indicated a range of removals between 75-96 percent.)

Ion exchange or reverse osmosis would be applicable to source waters with radium concentrations greater than 25 pCi/l up to 50-100 pCi/l.

In designing a water treatment system with a treatment capacity of 0.5 MGD or less, the availability of commercial equipment is a major constraint because custom designed and constructed installations are generally not cost effective. Lime or lime-soda softening systems are commercially available for systems greater than about 75,000 gpd. Ion exchange and reverse osmosis systems are commercially available for the very smallest (about 100 gpd or less) to the larger (greater than 0.5 MGD) system sizes.

WASTE RESIDUE HANDLING

Each of the radionuclide removal processes previously described generates a waste stream of some sort. These waste streams include lime and lime-soda softening sludge and backwash water, ion-exchange brine and resin rinse water, and reverse osmosis reject water.

These wastes are not under the jurisdiction of the Federal Nuclear Regulatory Commission (NRD) because they are naturally occurring. In addition, the radionuclide content of these waste streams is well below the level of radioactive wastes regulated by the NRC for those wastes where they do have jurisdiction.

The wastes still, however, must be handled in an environmentally acceptable manner. Available options for waste residue handling and disposal should be considered when selecting a treatment process for radionuclide removal.

Federal and state National Pollutant Discharge Elimination System (NPDES) regulations apply if the waste streams are discharged to a navigable waterway. EPA or primacy state permits are required for such discharges. Waste residue injected underground is regulated under the authority of the Safe Drinking Water Act's Underground Injection Control (UIC) program. Disposal by deep well injection requires a permit which is issued by EPA or primacy state authorities.

Landfilling or land application of water plant wastes is not currently regulated under the federal Resource Conservation and Recovery Act's (RCRA) Hazardous waste management program. Land disposal of such wastes is generally regulated under the jurisdiction of state and local regulatory agencies who should be consulted prior to choosing a treatment process alternative.

COST ESTIMATING PROCEDURES AND FUNDING SOURCES

Section VI of this document provides a procedure for estimating costs for radionuclide removal. It begins with an explanation of construction costs, their annualization and adjustment for inflation. Operation and maintenance costs are then discussed. A method for determining total annual costs and costs per thousand gallons of product water is then provided.

Sources of financial assistance, in the form of loans, loan guarantees, or outright grants, are very limited. The principal federal financial assistance programs available are shown in Table 1-1.

PERSONNEL REQUIREMENTS FOR THE OPERATION AND MAINTENANCE OF RADIONUCLIDE REMOVAL SYSTEMS

For lime-soda softening, ion-exchange softening, or reverse osmosis treatment plants processing less than 0.5 million gallons per day (MGD), regular sampling and monitoring will be necessary to ensure continued reliable operation. The operator may or may not be required by the individual states to be full-time but can be expected to spend several hours at the plant each day for routine monitoring and preventive maintenance activities. The operator should have basic mechanical and electrical skills and should have a working knowledge of fundamental chemistry and be able to perform routine tests for hardness, alkalinity, pH and TDS, as well as be able to

TABLE 1-1

FEDERAL FINANCIAL ASSISTANCE PROGRAMS

Agency		Program Description
Farmers Home Administration	(1)	Cooperative grants up to 75 percent of project cost for publicly owned rural systems serving fewer than 10,000 persons.
	(2)	Loan guarantees up to 90 percent of loan face value for public or private rural utilities, emphasizing those serving fewer than 2,500 persons.
	(3)	Direct loans up to 75 percent of project cost.
Department of Interior	(1)	Direct loan programs for nonfederal entities in the 17 western states.
	(2)	Financial assistance for systems serving American Indians.
Small Business Administration	(1)	Loan guarantees up to 90 percent of face value, maximum $500,000, for privately owned utilities.

sample for radionuclides and interpret results from outside laboratories. To assist the operator in sampling, equipment lubricating, cleaning and maintenance, and general housekeeping, a maintenance helper or semiskilled laborer should also be available.

II. INTRODUCTION

Radionuclides are chemical elements which undergo spontaneous nuclear decay, thereby emitting various forms of radiation energy. They may originate from both natural and man-made sources. The National Interim Primary Drinking Water Regulations (NIPDWR) on radionuclides contain numerous technical terms which must be understood to determine whether the water supply is in compliance with the radionuclide regulations and to obtain maximum benefit from the treatment information presented in this document. A brief explanation of these terms and related concepts of radiation are presented in this section. The section is organized as follows:

- STRUCTURE OF MATTER
  - Atomic Notation
  - Radioactivity
  - Units of Radioactivity
- RADIONUCLIDES IN DRINKING WATER - OCCURRENCES AND SOURCES
  - Naturally Occurring Radionuclides
  - Man-made Radionuclides
- HEALTH EFFECTS OF LOW LEVEL RADIOACTIVITY IN DRINKING WATER
- FEDERAL REGULATIONS APPLICABLE TO RADIONUCLIDES IN DRINKING WATER
  - Monitoring Requirements
    - Natural Radioactivity
    - Man-made Radioactivity
  - Analytical Methods for Measuring Radioactivity

STRUCTURE OF MATTER

All matter is composed of basic substances called elements. There are 92 natural elements, including, for example: iron, hydrogen, oxygen, chlorine, sulfur and carbon. Each element has its own chemical characteristics, and cannot be separated into simpler substances by ordinary chemical means. An atom is the smallest unit of an element that possesses all the characteristics of the element.

Atoms are made up of fundamental particles called electrons, protons, and neutrons. The electron was first discovered as the basic unit of electricity. It is a very tiny, negatively charged particle considerably lighter than an atom. The proton is a positively charged particle having exactly the same magnitude of charge as the electron; however, it is much larger than the electron in mass, having approximately 1,840 times the electron mass. A neutron is a particle of neutral charge, and its mass is approximately equal to that of a proton.

An atom consists of a heavy concentration of mass at the center (the nucleus) surrounded by shells of electrons in different orbits. The primary constituents of the nucleus are neutrons and protons. Since the orbital electrons have a negative charge and are equal in number to the protons, the atom is neutral in overall charge. The atoms of all of the known elements can be organized according to the structure of their nuclei. The simplest atom known is hydrogen. It contains only one proton as its nucleus and, therefore, has only one electron in orbit around the nucleus (see Figure 2-1). The next simplest atom is helium. It contains two protons in its nucleus along with two neutrons and has two electrons in orbit (see Figure 2-1). Through years of research, scientists have discovered that electrons in orbit exist in certain arrangements. Electron configuration gives the atom properties which determine its chemical reactivity, ranging from nonreactive to highly reactive. Based on this discovery (which resulted in the identification of electron "shells" and "orbits") elements can be grouped into chemical families. For example, the lithium atom, shown in Figure 2-2, which has three protons and four neutrons in the nucleus, has two electrons in one orbit and a third in an outer orbit. This atom is relatively reactive chemically. Other atoms with a single outer electron; such as hydrogen, sodium, potassium, rubidium and cesium, have chemical properties similar to (but not identical with) those of lithium. Radium, which has two outer electrons, is chemically similar in behavior to calcium, which also has two outer electrons. For example, radium, like calcium, becomes incorporated into material such as bone when ingested by humans.

Only a certain number of positions in each orbit are available for electrons to occupy. Electrons of an atom tend to occupy all available positions in an orbit until its electron capacity is achieved. Higher orbits are then filled in succession. By putting more energy into the atom, electrons can be made to move to outer (higher energy state) orbits, leaving some lower energy level positions unoccupied. The atom is then said to be in an "excited" state. From here, electrons will spontaneously "fall" to lower orbits, much like water flows downhill, until the lower energy level orbits are all filled and the atom returns to its normal state. The energy lost in this process is emitted as high energy electromagnetic radiation, such as visible light or x-rays. An example of this concept is a neon lamp. The electric current passing through the neon gas knocks some of the electrons into higher shells, and as they return to their normal state, a characteristic light is given off. This phenomenon, however, accounts for only one kind of radiation and it is not generally the cause of the radioactivity encountered in drinking water supplies. To facilitate an understanding of these causes, some additional information about atomic structure is presented in the following subsections.

Atomic Notation

In order to simplify discussions concerning elements and atoms, a standard notational form is used to talk about atoms. It is based upon the primary characteristics of the atom. The first of these characteristics is the number of protons in the nucleus of the atom, as discussed earlier, which in a neutral atom is also the number of electrons contained in orbits around the nucleus. This number, which determines the element to which the atom belongs, is called the atomic number. This is a unique number for each and every element; in other words, each element is characterized by a nucleus which contains a specific number of protons. This establishes the chemical properties of each element.

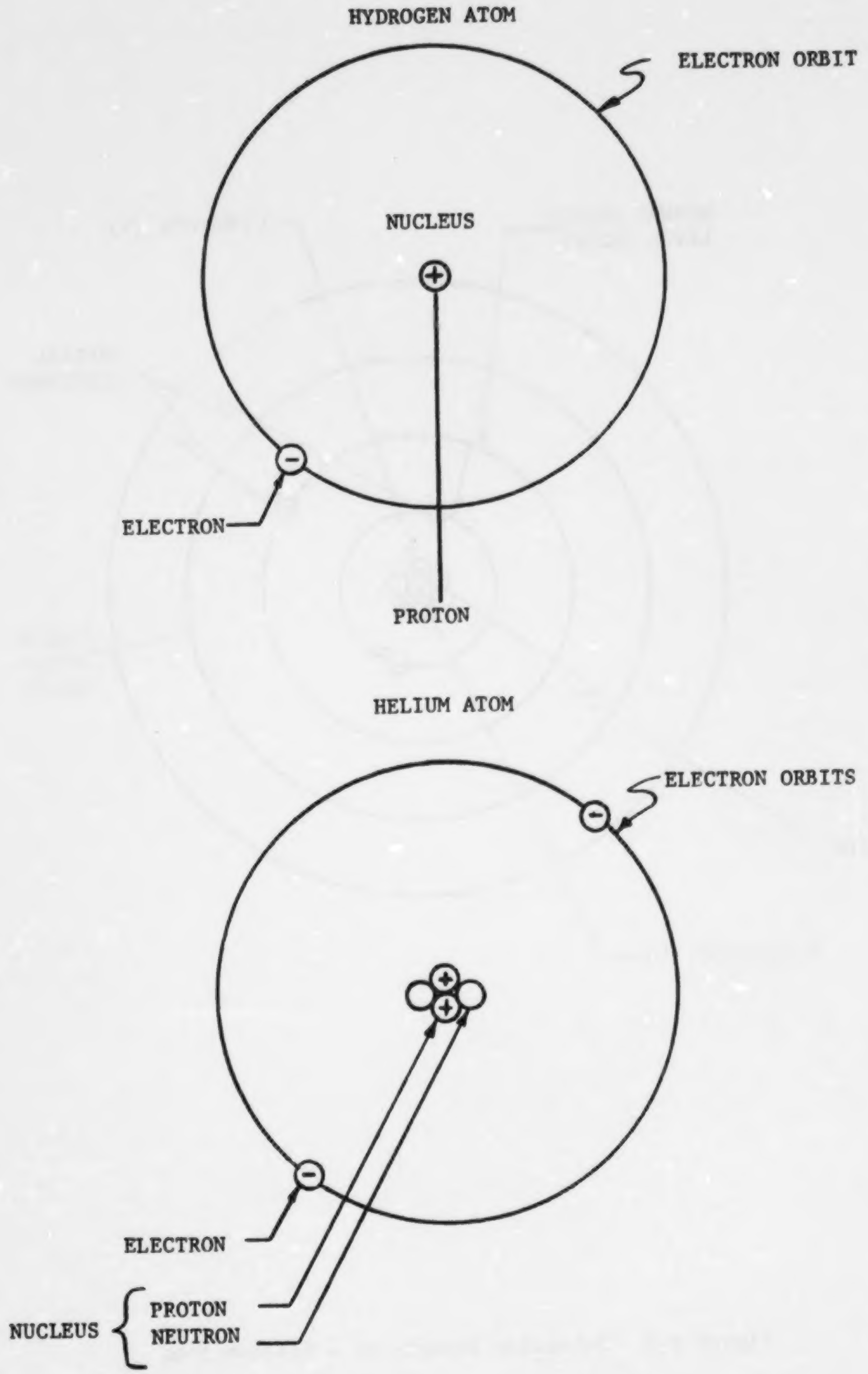
HYDROGEN ATOM
ELECTRON ORBIT
NUCLEUS
ELECTRON
PROTON
HELIUM ATOM
ELECTRON ORBITS
ELECTRON
NUCLEUS
PROTON
NEUTRON

Figure 2-1. Schematic Drawing of a Hydrogen Atom and a Helium Atom

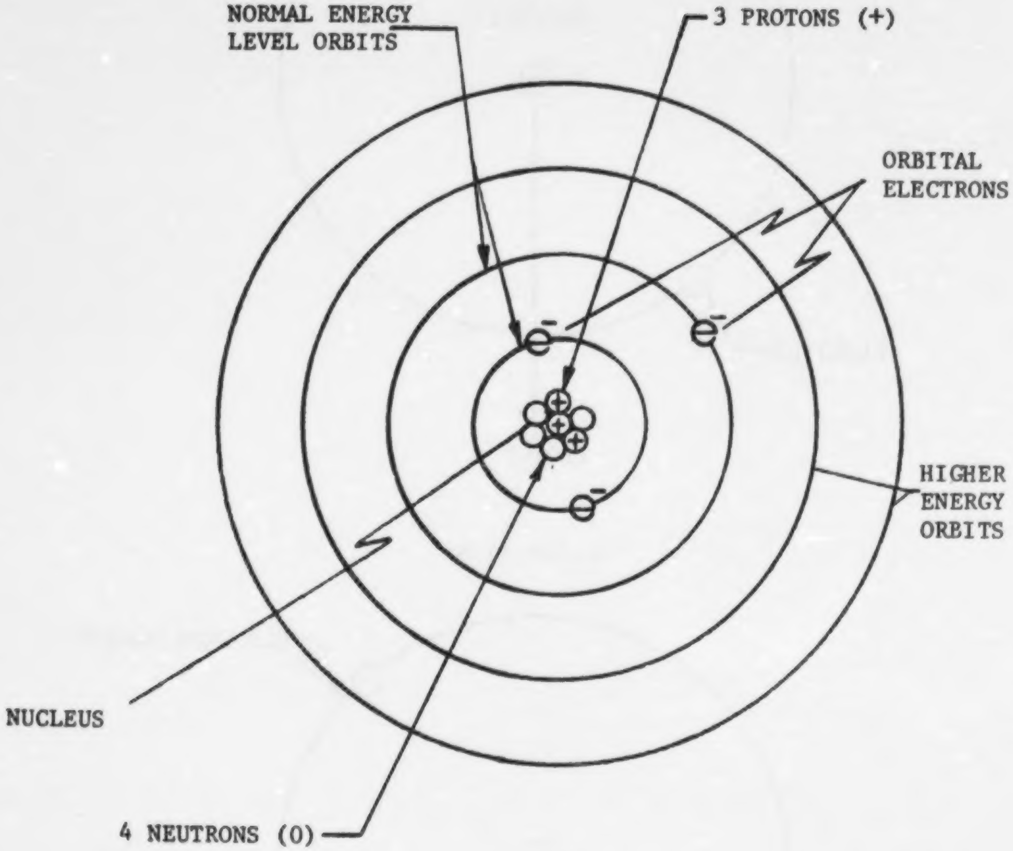
NORMAL ENERGY
LEVEL ORBITS
3 PROTONS (+)
ORBITAL
ELECTRONS
HIGHER
ENERGY
ORBITS
NUCLEUS
4 NEUTRONS (0)

Figure 2-2. Schematic Drawing of a Lithium Atom

The second primary characteristic is the number of neutrons in the nucleus, a factor which to some degree determines the nuclear characteristics of the atom. Variation in the number of neutrons does not change the chemical properties (the element is the same because the number of protons has not changed) but it produces considerable change in the stability of the element in regard to its tendency for radioactive decay. Atoms with the same number of protons but different number of neutrons are called isotopes. Not all isotopes of an element are radioactive, but some are. The total number of protons and neutrons in the nucleus is called the atomic mass number. The atomic mass number is used to label and distinguish isotopes of the same element, which have the same atomic number (number of protons in the nucleus).

For example, if an atom has 88 protrons, it is radium, whose chemical symbol is Ra. There are two well known isotopes of Ra: one contains 138 neutrons, the other 140 neutrons. Since the atomic mass number is the total number of protons and neutrons in the nucleus, the two isotopes of Ra have atomic masses of:

$$88 + 138 = 226, \text{ and}$$
$$88 + 140 = 228.$$

Since the atomic number is the number of protons in the nucleus, and this is unique for each element, it becomes synonymous with the element's name. Symbolically, the Ra isotopes can be uniquely identified in shorthand notation as:

^{226}Ra and ^{228}Ra.

It is also common and acceptable to write these abbreviations as: Ra^{226} and Ra^{228}, or Ra-226 and Ra-228. The latter form is used when superscripts are awkward.

Atomic mass numbers determined using the total number of protons and neutrons in the nucleus, are not the exact masses of the atom. Although they only reflect the total number of protons and neutrons, they do, however, provide a rough approximation of the actual masses. The atomic mass number is used to determine the energy released in radioactive reactions in accordance with Einstein's well known equation -- $E = MC^2$, which relates the energy available from nuclear transformations to the change in mass of the nucleus.

Radioactivity

Considerable energy is stored in the nucleus of an atom. Certain types of nuclei are by nature unstable. These unstable nuclei can attempt to reach a stable state by giving up some of their energy, or more technically, by emitting radiation. Three basic types of radiation are usually emitted: alpha (α), beta (β), and gamma (γ). Table 2-1 summarizes these three types of radiation.

Alpha and beta radiations are actually particles. The alpha particle is a close combination of two protons and two neutrons. It is thus positively charged (+2) and is in effect a fast-moving helium nucleus. In fact, when an alpha particle is slowed down enough, it will pick up two stray electrons and become a helium

TABLE 2-1

TYPES OF NUCLEAR RADIATION

Radiation Type	Emitted Particles	Process	Symbol
alpha particle	helium nucleus (two protons plus two neutrons)	alpha decay	α
beta particle	nuclear electron	beta decay	β
gamma ray	high energy electromagnetic radiation	gamma decay	γ

atom. The range of an alpha particle in air is only about 5 centimeters. The beta particle is really nothing more than a fast-moving electron which is ejected from the nucleus of an atom. Like all electrons, it has a negative charge. It has a range, dependent upon its energy, of about 5 meters in air. On the other hand, gamma radiation is a form of electromagnetic radiation similar to x-rays. It is a very high-energy, high-frequency radiation, which cannot be easily stopped or absorbed. Like x-rays, gamma rays have very strong penetration ability. Their range in air is hundreds of meters.

Alpha radiation occurs when an alpha particle is emitted from the nucleus of an atom, by a process known as alpha decay. Beta radiation occurs when a beta particle is emitted from a neutron in an atom's nucleus. The neutron decays into a high energy electron (beta particle) and a proton which remains in the nucleus. These decay processes which change the number of protons remaining in the nucleus result in the formation of a new element as a result of the radioactive emission (since the number of protons in the nucleus changes). Gamma radiation is the result of electromagnetic effects which may be thought of as changes in the charge and current distributions of the nuclei. Gamma radiation, although resulting in restructuring of the electomagnetic properties of the nucleus, does not result in formation of a new element.

Unlike gamma decay, alpha and beta decay leads to the formation of different elements. The isotope that decays is called the parent. The resulting isotope (a different element) is called the daughter. For example, Ra-226 decays by emitting an alpha particle. In this process the atomic mass number is reduced by 4 (an alpha particle consists of two protons and two neutrons) to 222 while the number of protons is reduced by 2 to 86. Therefore, the daughter formed is Radon (Rn). Rn is also radioactive and also decays (at a different rate) by the emission of an alpha particle to form the daughter polonium (Po), with the atomic number 84 and atomic mass of 218. These reactions can be written in shorthand fashion as follows:

$$^{226}_{88}\mathrm{Ra} \longrightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He}$$

$$^{222}_{86}\mathrm{Ra} \longrightarrow {}^{218}_{84}\mathrm{Po} + {}^{4}_{2}\mathrm{He}$$

where the atomic number and atomic mass numbers have been included and the alpha particle is written as helium with its atomic number and mass number. Note that the atomic numbers and atomic mass numbers balance (sum to the same total) on each side of the equations. Beta decay causes the atomic number to increase by one and can be described as the conversion of a neutron in the nucleus to a proton and the emission of an electron. An example of beta decay is $^{228}_{88}\mathrm{Ra}$ which decays to actinium ($^{228}_{89}\mathrm{Ac}$). This reaction is written:

$$^{228}_{88}\mathrm{Ra} \longrightarrow {}^{228}_{89}\mathrm{Ac} + \beta^{-}$$

where the greek symbol β^{-} is used to designate the beta particle and the minus sign shows that it is an electron. The atomic numbers and atomic mass numbers again balance since the atomic number for an electron is -1 and its atomic mass number is zero. Gamma decay changes neither the atomic number nor the element; it only involves a loss of energy. Alpha, beta, and gamma radiations have many different energies and masses and thus produce different effects as they interact with matter. Each is capable of knocking an electron from its orbit around the nucleus and away from the atom in a process called ionization. Ionized particles can be detected with relative ease and are therefore used to indirectly measure ionizing radiation. Radiation can also be nonionizing. Nonionizing radiation includes light, microwaves, and radio waves. Both ionizing and nonionizing radiations can be beneficial or harmful to humans.

In addition to their different methods of decay, different isotopes decay at different rates. The different rates of decay are characteristic to each isotope. The concept of half life is used to quantitatively describe these differences. The half life of an isotope is the time required for one half of the atoms present to decay. Half lives can range from billions of years or more (the half life of uranium-238 [U-238] is 4.5×10^{9} yr) to millionths of seconds (the half life of polonium-214 [Po-214] is 164×10^{-6} sec) and even less.

Another way to describe the differences between the nuclear radiations is their ability to penetrate matter. A comparison is shown in Figure 2-3. In general, most alpha particles can be stopped by a piece of aluminum foil while most gamma rays can pass through the human body (as do x-rays). The fact that the alpha particle can be stopped in such short distances, shows that it deposits more of its energy in a small distance; thus it is capable of doing more damage per unit volume than the other radiations, which is why alpha radiation is primarily of concern when inhaled or ingested.

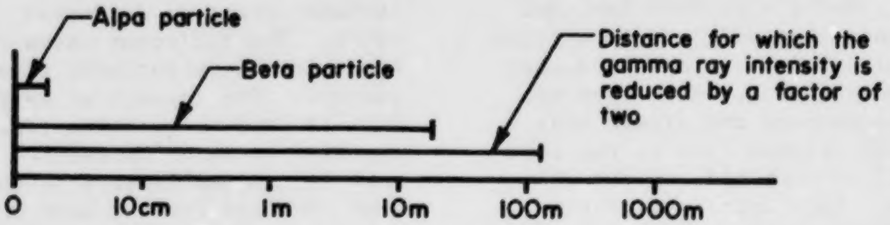

Figure 2-3. Range of Nuclear Particles in Air With the Same Energy (3 MEV). Note that the scale is logarithmic.

Many isotopes such as potassium-40 (K-40) found in human bodies, the carbon-14 (C-14) produced by cosmic rays and used to date old manuscripts, and the naturally occurring radioactive series exist naturally. There are three naturally occurring radioactive series: the uranium (U), thorium (Th) and actinium (Ac) series. These include a sequence of alpha, beta, and gamma decays involving the heavy nuclei of these elements. The series start with U-238, Th-232 and U-235, respectively, and all end with a different stable isotope of lead (Pb). In the middle of each series a different isotope of Rn is formed which accounts for its prevalence.

Units of Radioactivity

Generally, units such as milligrams per liter (mg/l), micrograms per liter (ug/l), or parts per million (ppm) are used to describe the concentrations of pollutants, toxic or hazardous substances based on their chemical properties. For the radionuclides, it is their radioactive properties and their relation to dosage and exposure that are of primary concern.

When determining the potential effect of radioactivity on human health, the number of alpha, beta, and gamma particles is more important than the mass of radionuclide. Thus, it is essential to have a unit that expresses the activity or number of particles emitted. The activity is related to the half life, and longer half lives mean lower activity. The curie is the term used to express this activity and is that quantity of a radionuclide that results in 3.7×10^{10} decays, disintegrations, or emissions per second. By definition, one gram of radium is said to have 1 curie (1 ci) of activity. By comparison, 1 gm of U-238 has an activity of 0.36 millionths of a curie (or 0.36 microcurie).

Terms or units that are used to describe radioactivity dosage or adsorbtion are described in Table 2-2.

Further discussion on unit measures of radioactivity, and methods to calculate dosage, are presented in the Appendix.

RADIONUCLIDES IN DRINKING WATER--OCCURRENCES AND SOURCES

Naturally Occurring Radionuclides

Radium is the most common radionuclide of current concern found in water sources in the United States. It is found particularly throughout the Midwest and parts of Florida. Numerous studies on ground-water supplies in areas of radium-bearing deposits have shown average radium concentrations of about 0.5 picocuries per liter (pCi/l). A picocurie is 1.0×10^{-12} curie. Maximum concentrations, however, exceed 50 pCi/l. Elevated levels of radium in ground water in Iowa and Illinois are thought to be caused by the leaching of radium from radium-bearing rock strata into the deep sandstone aquifers. In parts of Florida, elevated levels are caused by leaching of radium from phosphate rock deposits into the Floridan aquifer. High radium levels have also been found in surface runoff water in the vicinity of uranium-rich deposits in Colorado and New Mexico.

TABLE 2-2

RADIOACTIVITY TERMS

Term	Definition
Roentgen	A unit of energy flux used to describe the rate of exposure to X or gamma rays.
rep	The amount of energy adsorbed by tissue as a result of radiation.
rad	The amount of energy adsorbed by any medium as a result of radiation.
rem	The adsorbed dose of radiation in rads times the ratio of the biological effectiveness of the radiation considered to that for 200 kilovolt potential x-rays (relative biological effectiveness [RBE]).

EPA (EPA-470/9-76-003) has estimated that as many as 500 United States public water supplies may exceed the 5-pCi/l radium MCL. Most of these are ground-water supplies serving small systems of 0.5 million gallons per day (MGD) or less.

Chemically, radium is a metal, and a member of the group of metals which include magnesium, calcium, strontium, and barium. These metals show similar chemical behavior; thus, radium is transported in the environment in a manner similar to that of calcium and magnesium. For example, both calcium and radium, when ingested by humans, are deposited in the bones. Treatment techniques for removing radium from water supplies are similar to techniques used to soften (remove calcium and magnesium from) hard water. In water, radium generally loses its two outer electrons and occurs as Ra^{+2}. The two chemically similar isotopes of radium, Ra-226 and Ra-228, exist in potable water supplies. Ra-226, is an alpha particle emitter; Ra-228 is a beta particle emitter.

Uranium, another naturally-occurring radionuclide, is present in uranium-rich sandstone and shales in Colorado, New Mexico, and other western states, and is also found in phosphate rocks in the phosphate deposits of central Florida. Uranium can be found at picocurie per liter (pCi/l) levels in most U. S. surface and ground waters, although it is somewhat more common in ground waters. The average concentration of uranium in United States water supply sources has been determined by EPA in a recent study under Interagency Agreement No. EPA 79-D-X0674 to be about 1.73 pCi/l, with a range of from 0.07 to 652 pCi/l. EPA estimates that from 0.1 percent to 3 percent of the 40,000 community water systems in the U. S. contain in excess of 10 pCi/l uranium. Most of the systems with high uranium levels are expected to be small systems of less than 0.5 MGD located in the western states.

Uranium, a heavier element than radium and less chemically active, is generally found in natural waters in a complex ionic form. The particular form of a uranium-containing ion found in a natural water is known to vary with pH. At the pH of most natural waters, between 6 and 8 or above, the uranyl carbonates ($UO_2CO_3 \cdot 2K_2CO_3$) and ($UO_2CO_3 \cdot 2NO_2CO_3$) predominate. Uranium usually occurs naturally as the alpha particle emitting isotopes U-238 and U-234.

One other naturally occurring radioactive element which may be present in water supplies deserves brief mention - the element Radon.

Radon, a noble (highly stable and inert chemically) gas, occurs in nature from the radioactive decay of uranium and radium. All three of the common radioisotopes of radon (Rn-219, Rn-220, and Rn-222) are alpha emitters. Although rarely present in community water supplies at levels which would cause concern, radon, when present in drinking water, is generally found in dissolved form in ground waters. It may be removed from drinking water supplies by gentle aeration. Because so little is presently known about radon occurrence, it is being investigated further.

Man-made Radionuclides

Man-made radionculides may occur in drinking water sources as a result of fallout associated with nuclear weapons testing or through accidental discharges from industrial, commercial, or nuclear power facilities. Man-made radionuclides are primarily beta or gamma emitters. Strontium-90 and tritium are the most common man-made radionuclides found in surface waters. They generally occur as a result of fallout from nuclear weapons testing. The maximum contaminant levels contained in the National Interim Primary Drinking Water Regulations are well above the range of concentrations of these radionculides which currently exist in United States waters. Available data indicate strontium-90 concentrations are 1 pCi per liter, corresponding to a dose equivalent to bone marrow of less than 0.5 millirem annually. Tritium concentrations in surface water rarely exceed 1,000 pCi per liter, corresponding to a dose equivalent of less than 0.2 millirem per year.

As stated in EPA 570/9-76-003, EPA does not expect the maximum contaminant levels for radioactivity would apply to one-time situations such as might follow a major contaminating event. In accident situations it is necessary to balance, on a case-by-case basis, the potential risk from radiation exposure against the practicality, and consequences of any measures taken to reduce that risk. In such situations Federal guidance published in the Federal Register Notices of August 22, 1964 and May 22, 1965 apply and the emergency plans of the States, as provided for in Section 1413(A)(5) of the Safe Drinking Water Act should reflect this Federal Guidance.

HEALTH EFFECTS OF LOW LEVEL RADIOACTIVITY IN DRINKING WATER

Human bodies may be exposed to both external and internal radioactivity. Internal exposure occurs when drinking water is consumed or air containing radionuclides is inhaled. When a radioisotope enters the body by ingestion or inhalation (in the case of a gas such as radon), it will concentrate at some place in the body depending on its properties. The radionuclide may remain for relatively long periods of time, in some substances, i.e. bone, whereas it will pass through others quickly. Adverse health effects in humans result from the ionizing effect of radiation which causes damage to internal organs and tissue.

The National Academy of Science reports that radiation may cause cancer of virtually any type or at any place in the body given the right conditions of irradiation and host susceptibility. The primary basis for the EPA radionuclide regulations for drinking water is the carcinogenic (cancer causing) potential of this material.

Ionizing radiation damage in humans can also cause genetic-defects (abnormalities in future generations). There appears to be no completely safe lower limit of exposure to any radionuclide; however human consumption of potable water which contains radionuclides at levels below MCLs allowed by the National Interim Primary Drinking Water Regulations (NIPDWR) results in very low health risk.

FEDERAL REGULATIONS APPLICABLE TO RADIONUCLIDES IN DRINKING WATER

The present regulations covering radioactivity were promulgated July 9, 1976 in the Federal Register (Vol. 41, No. 133, pages 28404-28409). The present discussion provides only a simplified description of these regulations. It should not be used for legal purposes in lieu of the actual regulation.

The maximum contaminant levels for radionuclides in drinking water are 5 pCi/l of radium (combined Ra-226 and RA-228), 15 pCi/l of gross alpha particle activity (all sources of emitters except uranium and radon), and a total dose equivalent of 4 millirem (mrem)/yr for man-made radioactivity. Table 2-3 summarizes the radionuclide MCLs.

Uranium and radon are both excluded from the current regulations but it is anticipated that they may be regulated in the future. Uranium was excluded because its regulation is complicated because uranium is both chemically and radiologically toxic. A nonfederally enforceable guidance limit of 10 pCi/l is being considered for uranium. Radon is excluded because it is a gas, and has rarely been found present in water at concentrations high enough to exceed the MCL for alpha emitters. When radon, a chemically unreactive heavy gas, leaves the water and enters the surrounding air, it accumulates in buildings or other enclosed spaces where it may be inhaled by humans, causing concern to health officials. This problem with radon is not thought to be wide-

TABLE 2-3

SUMMARY OF NIPDWR FOR RADIONUCLIDES

MAXIMUM CONTAMINANT LEVELS FOR RADIUM-226, RADIUM-228, AND GROSS ALPHA PARTICLE RADIOACTIVITY (excluding radon and uranium)

Combined Ra-226 and Ra-228	5 pCi/l
Gross alpha particle activity	15 pCi/l

MAXIMUM CONTAMINANT LEVELS FOR BETA PARTICLE AND PHOTON RADIOACTIVITY FROM MAN-MADE RADIONUCLIDES

The average annual concentration of beta particle and photon radioactivity from man-made radionuclides in drinking water shall not produce a total body or internal organ dose equivalent greater than 4 mrem per year. For the radionuclides tritium and strontium, the MCLs corresponding to the dose equivalent requirements are:

Tritium (total body)	20,000 pCi/l
Strontium-90 (bone marrow)	8 pCi/l

Source: Federal Register, 1976 (Vol. 41, No. 133, pages 28404-28409)

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spread, however, and control of radon in the air is not part of the current National Interim Primary Drinking Water Regulations.

Monitoring Requirements

Compliance is based on the analysis of an annual composite of four consecutive quarterly samples, or the average of the analyses of four samples obtained at quarterly intervals. This analysis to determine compliance must be repeated every four years under ordinary operating conditions. However, the procedure must be repeated upon any major change in the water supply or addition of new water sources. In addition to the sampling and analytical program described above, each state may require further monitoring for water supply systems located near nuclear facilities.

Natural Radioactivity

The determination of concentrations of natural radioactivity begins with the measurement of the gross alpha particle activity, which using current analytical techniques measures the total of all alpha emitters except radon. This measurement is used as a screening technique. If the gross alpha particle activity is less than 5 pCi/l, the sample is in compliance. If the gross alpha particle activity is greater than 15 pCi/l the maximum contaminant level (MCL) may be exceeded and a decision scheme is followed as shown in Figure 2-4 to determine if the water exceeds the MCL.

The first step in the decision scheme is to measure uranium (which is not regulated under the NIPDWR) and to subtract its activity from the gross alpha count. If the resultant activity is greater than 15 pCi/l, the source is not in compliance. If the resultant activity is less than 5 pCi/l, the source is in compliance.

If the gross alpha particle activity is greater than 5 pCi/l, the activity of Ra-226 must be determined. Then, if the Ra-226 concentration is greater than 3 pCi/l, the RA-228 activity must be determined. The total of Ra-226 and Ra-228 must not exceed 5 pCi/l (the MCL for radium) for the source to be in compliance.

Man-made Radioactivity

The measurement of man-made radioactivity levels is required for surface water treatment systems that serve more than 100,000 people. The gross beta particle activity is used as a screening technique (see Figure 2-5). If the gross beta particle activity is less than 50 pCi/l, then just tritium and strontium-90 (Sr-90) activities must be determined. These isotopes must be measured individually because the test method for gross beta does not measure either tritium or strontium-90. Tritium is determined by liquid scintillation. Dissolved strontium-90 is determined by beta counting after a lengthy chemical separation procedure that removes other fission products. SR-90 is one of the most toxic fission products, and therefore its concentration is limited to 8 pCi/l. As shown in Figure 2-5, H-3 (tritium) must be less than 20,000 pCi/l and SR-90 less than 8 pCi/l for the water supply to be in compliance. In addition, the combination of these two must not result in an absorbed dose exceeding 4 mrem/yr.

To determine the total dose, the relationship that 20,000 pCi/l for H-3 results in a dose of 4 mrem/yr and that 8 pCi/l for Sr-90 also results in a dose of 4 mrem/yr must be used. The dose resulting from combinations of these radionuclides at various concentrations can be determined by simple proportion. For example:

-- 15,000 pCi/l of H-3 (or, 75% of 20,000 pCi/l) results in a dose of 3 mrem/yr (or, 75% of 4 mrem/yr).

-- 6 pCi/l of Sr-90 (or, 75% of 8 pCi/l) results in a dose of 3 mrem/yr (or, 75% of 4 mrem/yr).

Thus, in the above example, each radionuclide individually would pass the first two tests (i.e., result in a dose less than 4 mrem/yr), but together they would exceed the limit, and the water would not be in compliance with the MCL.

If the gross beta particle activity is greater than 50 pCi/l, then the water sample must be analyzed

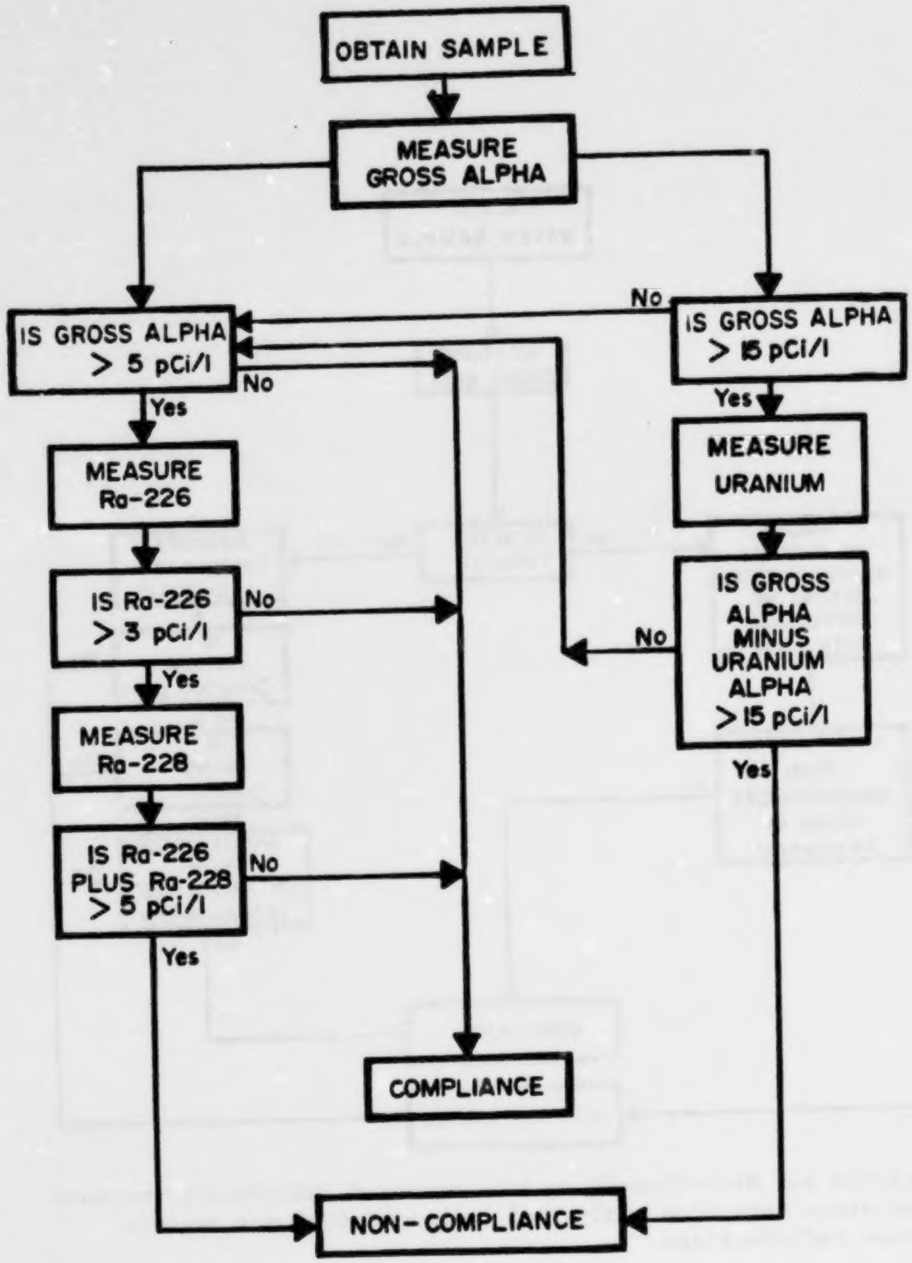
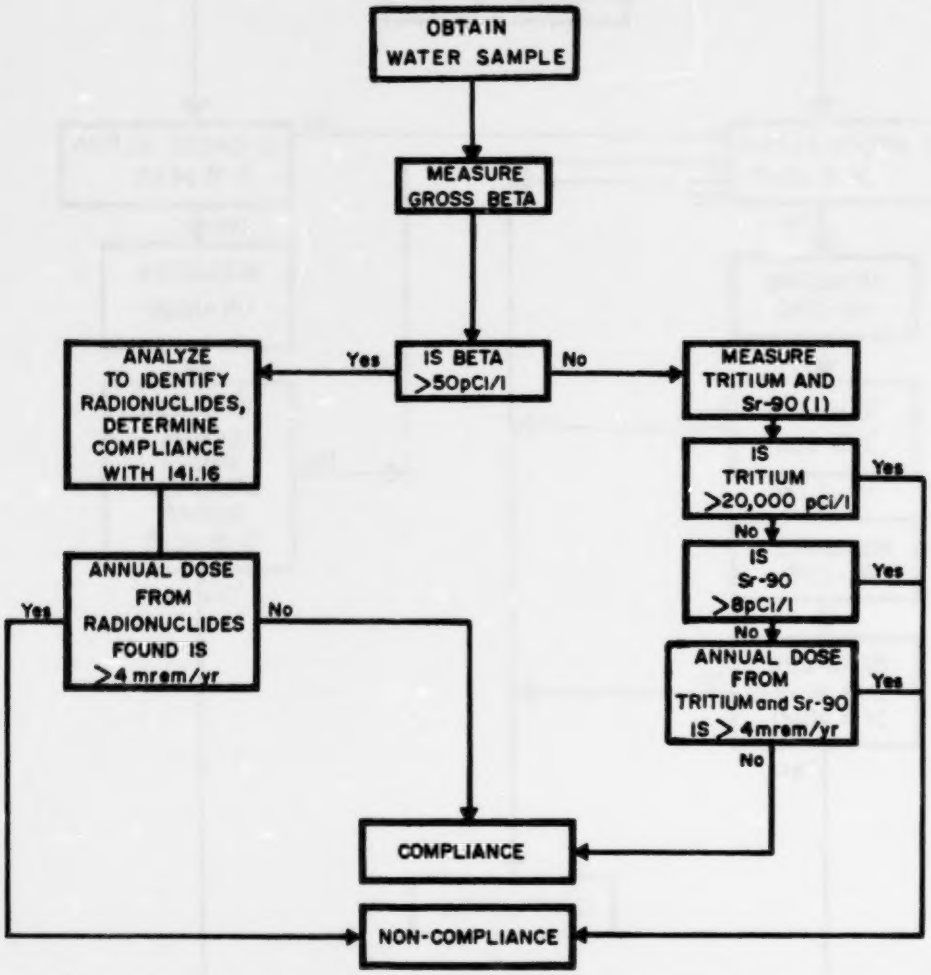

OBTAIN SAMPLE
MEASURE GROSS ALPHA
IS GROSS ALPHA > 5 pCi/l
No
Yes
IS GROSS ALPHA > 15 pCi/l
No
Yes
MEASURE Ra-226
MEASURE URANIUM
IS Ra-226 > 3 pCi/l
No
Yes
IS GROSS ALPHA MINUS URANIUM ALPHA > 15 pCi/l
No
Yes
MEASURE Ra-228
IS Ra-226 PLUS Ra-228 > 5 pCi/l
No
Yes
COMPLIANCE
NON-COMPLIANCE

Figure 2-4. Flow Chart for Gross Alpha Particle Activity Monitoring (U.S. EPA, Las Vegas, Environmental Monitoring and Support Laboratory). Note that it is not an NIPDWR requirement that radon and uranium be measured if the gross alpha activity is greater than 15 pCi/l.



OBTAIN WATER SAMPLE
MEASURE GROSS BETA
IS BETA >50pCi/l
Yes
No
ANALYZE TO IDENTIFY RADIONUCLIDES, DETERMINE COMPLIANCE WITH 141.16
MEASURE TRITIUM AND Sr-90 (1)
IS TRITIUM >20,000 pCi/l
Yes
No
IS Sr-90 >8pCi/l
Yes
No
ANNUAL DOSE FROM TRITIUM and Sr-90 IS > 4mrem/yr
Yes
No
ANNUAL DOSE FROM RADIONUCLIDES FOUND IS >4 mrem/yr
Yes
No
COMPLIANCE
NON-COMPLIANCE

(1) Tritium and Strontium-90 must be measured individually because the gross beta scan analytical technique does not measure these radionuclides.

Figure 2-5. Flow Chart for Gross Beta Particle Activity Monitoring for a Water Source not Designated as Being Contaminated by Effluents From Nuclear Facilities Serving More than 100,000 Persons as Designated by the State. (U.S. EPA Las Vegas, Environmental Monitoring and Support Laboratory)

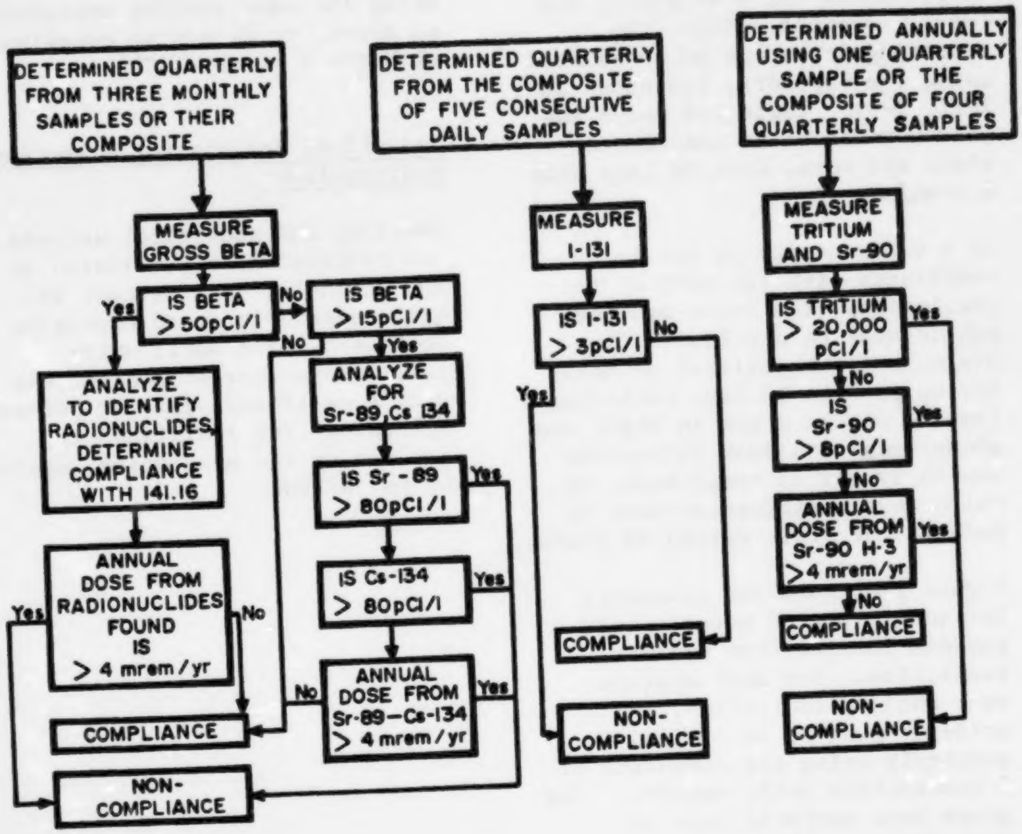

DETERMINED QUARTERLY FROM THREE MONTHLY SAMPLES OR THEIR COMPOSITE
MEASURE GROSS BETA
IS BETA > 50pCi/l
Yes
No
IS BETA > 15pCi/l
No
Yes
ANALYZE TO IDENTIFY RADIONUCLIDES, DETERMINE COMPLIANCE WITH 141.16
ANALYZE FOR Sr-89, Cs 134
IS Sr-89 > 80pCi/l
Yes
IS Cs-134 > 80pCi/l
Yes
ANNUAL DOSE FROM RADIONUCLIDES FOUND IS > 4 mrem/yr
Yes
No
ANNUAL DOSE FROM Sr-89—Cs-134 > 4 mrem/yr
No
Yes
COMPLIANCE
NON-COMPLIANCE
DETERMINED QUARTERLY FROM THE COMPOSITE OF FIVE CONSECUTIVE DAILY SAMPLES
MEASURE I-131
IS I-131 > 3pCi/l
No
Yes
COMPLIANCE
NON-COMPLIANCE
DETERMINED ANNUALLY USING ONE QUARTERLY SAMPLE OR THE COMPOSITE OF FOUR QUARTERLY SAMPLES
MEASURE TRITIUM AND Sr-90
IS TRITIUM > 20,000 pCi/l
Yes
No
IS Sr-90 > 8pCi/l
Yes
No
ANNUAL DOSE FROM Sr-90 H-3 > 4 mrem/yr
Yes
No
COMPLIANCE
NON-COMPLIANCE

Figure 2-6. Flow Chart for Monitoring Drinking Water Samples Near a Nuclear Facility (U.S. EPA, Las Vegas, Environmental Monitoring and Support Laboratory)

to determine which radionuclides are present. This must be done to estimate the total dose since it is different for each radionuclide. The doses resulting from all these radionuclides cannot exceed 4 mrem/yr. The concentrations of the more important isotopes that result in a dose of 4 mrem/yr are listed in Appendix B.

As an example calculation, suppose that the results of analyses were Sr-90 = 2 pCi/l, Cs-137 = 50 pCi/l, Ba-131 = 60 pCi/l, and I-131 = 1 pCi/l. Then, the resulting doses can be calculated using the Appendix, (as shown in Table 2-4). Table 2-4 shows the source would be in compliance since the total dose is less than 4 mrem/yr.

If a water supply is not in compliance with any part of the regulations, the State and the public must be notified. The State is to be notified of monitoring results 10 days following the end of the month in which the measurement was made unless the source is not in compliance, in which case notification must be made to the State within 48 hours.

Figure 2-6 shows the procedure for monitoring of water supply systems located near nuclear facilities. For such systems near nuclear facilities, I-131 activity must be determined quarterly using the composite of 5 consecutive daily samples. The gross beta particle must be determined quarterly from three monthly samples or their composite. Annual monitoring for Sr-90 and H-3 is to be conducted using one of the quarterly samples or their composite.

If the gross beta particle activity exceeds 15 pCi/l for a water supply system near a nuclear facility, then Sr-89 and Cs-134 activities are sampled to assure that the sum of their resulting doses does not exceed 4 mrem/yr. These isotopes indicate recent contamination, such as from a nuclear facility, since they have short half-lives, and are not usually present in fallout. Where gross beta particle activity exceeds 50 pCi/l, individual radionuclides must be determined using the same summing procedure as above, to determine compliance with the 4 mrem/yr MCL.

Analytical Methods for Measuring Radionuclides

Sampling and analytical methods for radionuclides are listed in the Appendix. All methods require specialized and expensive equipment. The small water utility operator should consult with a certified state or private laboratory for assistance in conducting the monitoring required by the NIPDWR.

TABLE 2-4

EXAMPLE CALCULATION OF TOTAL DOSE FOR MAN-MADE RADIONUCLIDES

(1) Isotope	(2) Concentration (pCi/l)	(3) Concentration in pCi/l Yielding a Dose of 4 mrem/yr (From Appendix III)	(4) Resulting Individual Dose (mrem/yr)*
^{90}Sr	2	8	1.0
^{137}Cs	50	200	1.0
^{131}Ba	60	600	0.4
^{131}I	1	3	1.3
		TOTAL	3.7

* Method for determining resulting individual dose:

General formula:

$$\frac{\text{Actual Concentration pCi/l (2)}}{\text{Concentration yielding dose of 4 mrem/yr (3)}} \times \frac{4.0\ \text{mrem}}{\text{yr}} = \text{Resulting individual dose mrem/yr (4)}$$

Example calculation for Sr-90:

$$\frac{2\ \text{pCi/l}}{8\ \text{pCi/l}} \times 4.0\ \frac{\text{mrem}}{\text{yr}} = 1.0\ \frac{\text{mrem}}{\text{yr}}$$

III. NONTREATMENT AND TREATMENT ALTERNATIVES FOR REDUCING RADIONUCLIDE CONTAMINATION IN DRINKING WATER

If it has been determined that the concentration of radionuclides in the water supply exceeds allowable levels, two methods of solving this problem exist:

- Nontreatment alternatives
- Treatment alternatives, i.e., for radionuclide removal

Each is discussed in this section. Engineering and economic data which further aid in the analysis of treatment and nontreatment alternatives are given in Sections IV and VI, respectively.

Treatment data and design information in this manual are presented for the naturally occurring radionuclides, radium and uranium. As explained in Section II, the Introduction to this manual, the potential sources of man-made radionuclides are radioactive fallout and accidental release from nuclear facilities. The MCLs for strontium-90 and tritium, the major radionuclides from fallout which enter water supplies, are well above concentrations currently detected in U. S. water supplies. There is scant information available on the removal of these, or other man-made radionuclides from drinking water supplies. The MCLs for radionuclides do not apply to one-time situations such as might follow a major contaminating event. In such situations, Federal guidance as published in the Federal Register Notices of August 22, 1964 and May 22, 1965 will apply. The emergency plans of the States, as provided for in Section 1413(A)(5) of the Safe Drinking Water Act, should follow the Federal guidance.

For those utilities interested in disaster planning, the Suggested Reading list in this manual contains several references for the emergency treatment of water supplies which have been contaminated by fallout or radionuclide release due to a major contaminating event.

NONTREATMENT ALTERNATIVES

Four options are covered in this category:

- Raw water source substitution
- Blending with water low in radionculides
- Connection to an existing regional system
- Organizing a regional system

Inherent in all of these options is the usually correct assumption that the radionuclide problem is localized. Thus, it may be possible to find acceptable water from other nearby wells or surface sources. Also, an existing well might be modified to draw water from different aquifers (water bearing levels). Surface water users may find it feasible to draw from other streams, or may find that relocation of the intake will solve the problem. Substitution of sources should receive top priority in the search for solutions. Since the MCLs for radionuclides apply to the water as it is delivered to the user, raw water which exceeds the standards may be used if it is blended with other supplies sufficiently low in contamination such that the resulting water meets the standards. For example, a water supply could be made up of equal quantities of two raw supplies containing 2 pCi/l and 8 pCi/l of radium, respectively, and still meet the 5 pCi/l standard for combined Radium 226 and 228.

It may also be cost effective to obtain all or at least a sufficient amount of water for blending from an outside supplier, perhaps a nearby city or regional system. Regional systems are becoming more attractive as their advantages become increasingly apparent. Larger systems can spread the costs of water quality monitoring and analysis, as well as operation and maintenance, over a larger user base, thereby lowering per capita costs. The analysis of nontreatment alternatives is not complete without investigating regionalization alternatives. Joining an existing regional system, or forming a new regional utility by joining with other nearby systems which may be having similar water quality problems should be considered.

A broad range of regionalization alternatives is explained in the following reference:

> Regionalization Options for Small Water Systems U. S. EPA Office of Drinking Water, 401 M Street, SW, Washington, DC 20460.

TREATING WATER SUPPLIES FOR RADIUM AND URANIUM REMOVAL

The concentration of radium in a drinking water supply can be reduced by any of the following treatment techniques:

- Lime or Lime-Soda Softening
- Ion Exchange Softening
- Reverse Osmosis

Uranium may be removed by either of the following treatment techniques:

- Anion (negatively charged ion) Exchange, or
- Reverse Osmosis

The applicability of these treatment techniques is summarized in Table 3-1. Considerable data are available about the treatment techniques listed for radium removal, including substantial data from full-scale operating plants. Much less information is available on the removal of uranium; however, recent laboratory-scale studies provide sufficient information to allow the preliminary selection of a treatment system for uranium removal. It is essential that prior to design and construction of a treatment system for uranium, a utility with elevated uranium levels in its drinking water conduct laboratory or pilot-scale tests on the specific raw water to be treated.

Pilot-scale studies are also recommended prior to final design of a system for radium removal, in order to ensure that the treatment system will achieve acceptable performance.

The softening methods are effective because radium is chemically similar to calcium and magnesium, the primary components of hard water. Reverse osmosis, a membrane technology used for desalting sea water or brackish water, is effective because it provides for

TABLE 3-1

TREATMENT TECHNIQUES APPLICABLE FOR REDUCING RADIUM AND URANIUM RADIONUCLIDES FROM DRINKING WATER

Treatment Technique	Radionuclide Removed	Approximate Range of Reduction Percent	Comments
Lime or Lime-Soda Softening	Radium	56-94	Considerable full-scale system data available
	Uranium	85-98	Requires pH above 10.6. Limited lab-scale data data available
Ion Exchange	Radium	90	Considerable full-scale system data available Cation exchange process
	Uranium	90	Limited lab-scale data available Anion exchange process High resin capacities reported
Selective Complexer	Radium	Unknown	Experimental technology currently being field tested by Dow Chemical
	Uranium	N/A	N/A
Reverse Osmosis	Radium	90	Limited full-scale data available
	Uranium	90	Limited lab-scale data available
Coagulation and Filtration	Radium	Minimal	Not applicable for radium removal
	Uranium	5-90	Limited lab-scale data available Uranium removals highly variable and dependent on pH and other water quality parameters High pH may be required for maximum removals, which is generally uncommon practice in coagulation

high levels of removal of nearly all dissolved ions in water, which would include radium.

Conventional treatment methods such as coagulation, settling, filtration, or chlorination, have little or no capability to remove radium from drinking water.

Coagulation using aluminum sulfate (alum) or lime/lime-soda softening have been shown in tests conducted by the Oak Ridge National Laboratory (ORNL) for EPA to be capable of reducing uranium concentrations under certain very specific conditions. These conditions include a pH of greater than 10.6 and the presence of relatively high magnesium and alkalinity concentrations. Although these conditions may exist in some lime or lime-soda softening plants, they are very uncommon in conventional coagulation applications. A survey conducted by ORNL for EPA of several existing coagulation and lime-soda softening plants throughout the United States in locations with elevated uranium concentrations demonstrated little or no uranium reduction. Although these plants were not being operated to achieve uranium reduction, the survey results of full-scale plants indicate that insufficient data are available to recommend conventional coagulation an filtration or lime/lime-soda softening for uranium removal, particularly if new construction is required.

A utility which must remove uranium and which currently treats its water using alum coagulation or lime softening might consider modification of its existing facilities to improve uranium removal. An expert water treatment consultant or engineer experienced in radionuclide removal should provide advice on such modifications. Optimization of alum coagulation or lime softening for uranium removal is very site-specific and requires complicated laboratory or pilot-scale testing which is beyond the scope of this manual.

Ion exchange can be used for uranium removal from drinking water when the proper anionic exchange medium is used because uranium is present in most natural waters as an anion (uranyl anion). Reverse osmosis is effective because it provides for high levels of removal of nearly all dissolved ions in water, including the uranyl ion.

Lime and Lime-Soda Softening

The hardness of most water supplies is caused by the presence of calcium and magnesium ions in solution. One method of softening water involves changing the calcium and magnesium compounds dissolved in water to an insoluble form, and then removing the insoluble compounds (precipitates) by sedimentation and filtration. This process is known as the chemical, or lime-soda softening process, since lime in the form of calcium oxide (quicklime) or calcium hydroxide (slaked or hydrated lime) is the most common chemical used to precipitate the hardness from drinking water. Radium, which is chemically similar to calcium and magnesium, is also precipitated and removed from water during the lime-soda process.

Process Description

Figure 3-1 shows a simplified schematic of the lime-soda softening process. It contains the following steps:

- Chemical feeding and mixing,
- Flocculation,
- Sedimentation,
- Recarbonation, and
- Filtration

During chemical feeding and mixing, lime, soda-ash, or caustic-soda are added to the raw water and rapidly mixed to ensure quick solution of all chemicals. During this operation, the pH of the raw water is raised and the chemical reactions which will remove some of the hardness and radium from the water begin.

During flocculation, the raw water is gently mixed. The purpose of this mixing is to assist the chemical reactions which cause the precipitation of insoluble calcium, magnesium, and radium compounds. It is not necessary to know the details of the many chemical reactions which take place in order to understand the basic lime-soda softening process. The Bibliography contains several references which explain in detail the chemistry involved. In order to illustrate the type of reactions which occur during the process, two representative reactions involving calcium are discussed.

Calcium ions (hardness) dissolved in water most often take the form of calcium bicarbonate $Ca^{++}(HCO_3^-)_2$. This is known as carbonate hardness. When lime is added to the water, the following reaction takes place:

$$\overset{\text{Lime}}{Ca^{++}(OH)_2^-} + \overset{\text{Calcium Bicarbonate}}{Ca(HCO_3)_2} \longrightarrow \overset{\text{Calcium Carbonate}}{2CaCO_3 \downarrow} + \overset{\text{Water}}{2H_2O}$$

The calcium carbonate formed in the reaction is a solid and precipitates, thereby removing both the original calcium ion which existed in the raw water and the calcium ion added with the lime.

If there is not enough alkalinity present in the raw water, some of the hardness is present as noncarbonate hardness. Soda ash (Na_2CO_3) must then be added in order that the solid calcium carbonate can be formed. This is why the process is referred to as the lime-soda process.

Magnesium and radium ions enter into similar reactions with lime and soda ash and form similar solid compounds. More lime must be added to remove magnesium than calcium because magnesium carbonate is a soluble compound and magnesium is precipitated as magnesium hydroxide, $Mg(OH)_2$. Any free carbon dioxide in the raw water will also react with the lime added and increase the lime requirements for softening. Chemical requirements for softening are presented in Section V.

Once the chemical reactions are complete, the precipitated solid compounds are removed from the water by sedimentation. It is usually easy to settle lime-soda softening precipitates because they are much denser than water.

Since the pH of a lime softened water is generally in the range

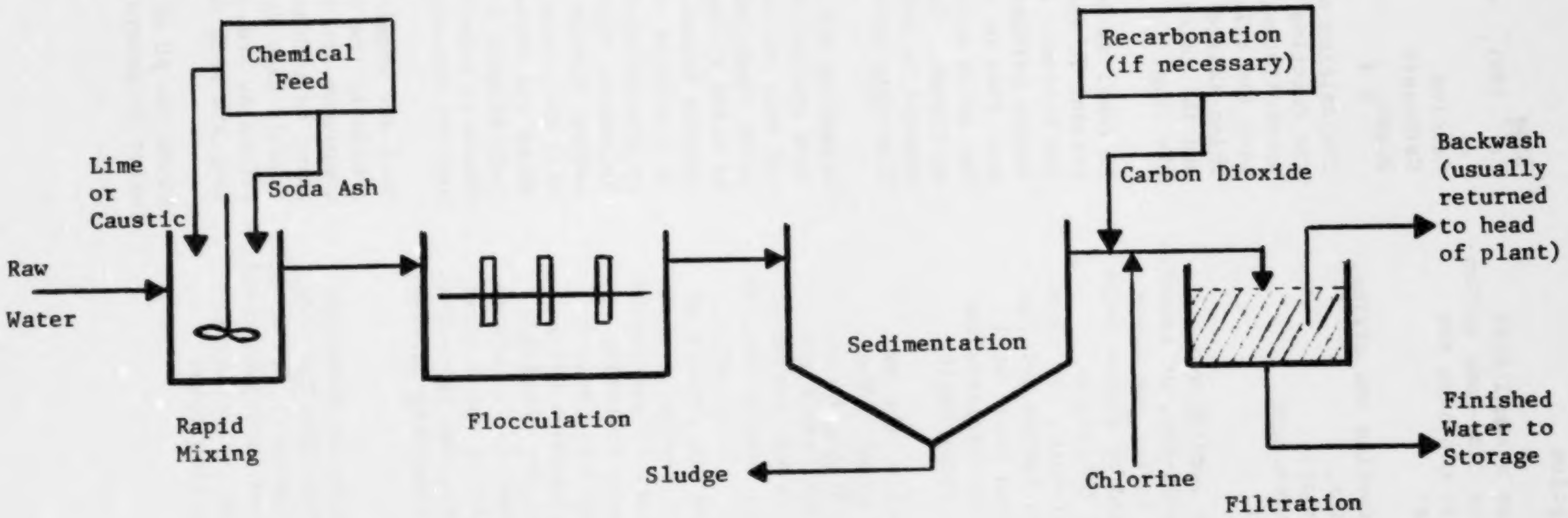

Chemical Feed
Lime or Caustic
Soda Ash
Raw Water
Rapid Mixing
Flocculation
Sedimentation
Sludge
Recarbonation (if necessary)
Carbon Dioxide
Chlorine
Filtration
Backwash (usually returned to head of plant)
Finished Water to Storage

Figure 3-1. Simplified Schematic of Lime-Soda Softening Process

of 8.5-11, the pH often must be readjusted to a lower value in order to prevent formation of a scale in the water distribution pipes. Sometimes the normal chlorination of the water for disinfection purposes will sufficiently lower the pH. Often, however, carbon dioxide must be added to the water following sedimentation in order to lower the pH. This operation, called recarbonation, may be accomplished by bubbling CO_2 gas through the water in a separate, small reaction basin.

Sometimes the chlorine added to the water for disinfection may decrease the pH to a stable value so that recarbonation is not necessary. Another alternative to stabilizing a lime softened water would be the addition of a commercial acid such as HCl or H_2SO_4 (hydrochloric or sulfuric acid, respectively).

The final operation in lime-soda softening is filtration. Filtration is a polishing step required to remove any unsettled solids from the water, thus providing a water which meets the turbidity regulation. Pressure filters are sometimes used for small systems. Larger systems use gravity-type rapid sand filters. A very common filter used for small lime-soda systems is a gravity-type filter which backwashes (cleans) itself automatically using a hydraulic arrangement.

A more detailed discussion of filtration methods, as well as detailed design procedures for filtration can be found in an EPA document titled Turbidity Removal for Small Public Water Systems.

Lime-Soda Softening Equipment

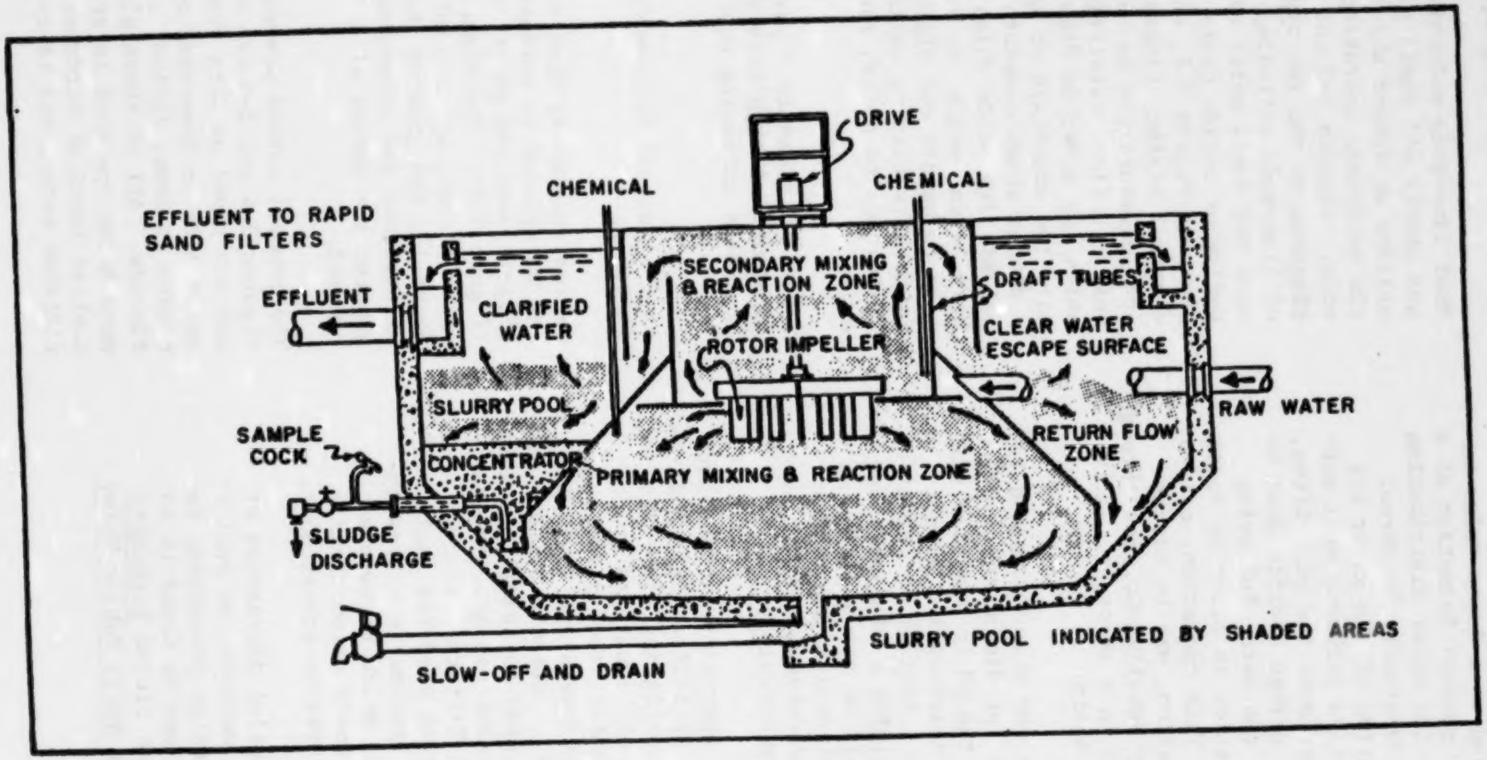
Most lime-soda softening plants, and nearly all small plants, utilize equipment which combines the necessary operations in one unit. Figures 3-2 and 3-3 show diagrams of the two typical types of lime-soda softening plants used for small water systems. Upflow or solids contact units, shown in Figure 3-2, combine chemical mixing, flocculation, and sedimentation in one physical unit. Upflow, catalytic softening units, as shown in Figure 3-3, have the advantage of generating a sludge which consists of hard, pellet-like beads which dewater rapidly and which are relatively easy to handle and dispose. Both types of softening units require filtration to polish the softened water.

Table 3-2 presents a partial list of equipment suppliers who provide lime-soda softening equipment.

Radium Removal by Lime-Soda Softening

Radium removal by lime softening can be related to hardness removal (Figure 3-4) and pH of treatment (Figure 3-5). The higher the pH of treatment, up to a pH of about 11, the greater the amount of hardness and consequently the greater the amount of radium removed.

The removal curves presented in Figures 3-4 and 3-5 are empirical and are based on data from full-scale lime or lime-soda softening plants in Iowa, Illinois, and Florida. All of these plants were being operated to produce a desired level of hardness in the finished water, not to optimize


DRIVE
CHEMICAL
CHEMICAL
EFFLUENT TO RAPID SAND FILTERS
EFFLUENT
SECONDARY MIXING & REACTION ZONE
DRAFT TUBES
CLARIFIED WATER
ROTOR IMPELLER
CLEAR WATER ESCAPE SURFACE
RAW WATER
SLURRY POOL
RETURN FLOW ZONE
SAMPLE COCK
CONCENTRATOR
PRIMARY MIXING & REACTION ZONE
SLUDGE DISCHARGE
SLURRY POOL INDICATED BY SHADED AREAS
SLOW-OFF AND DRAIN

Source: Infilco-Incremont Corporation.

Figure 3-2. Solids Contact or Upflow Plant

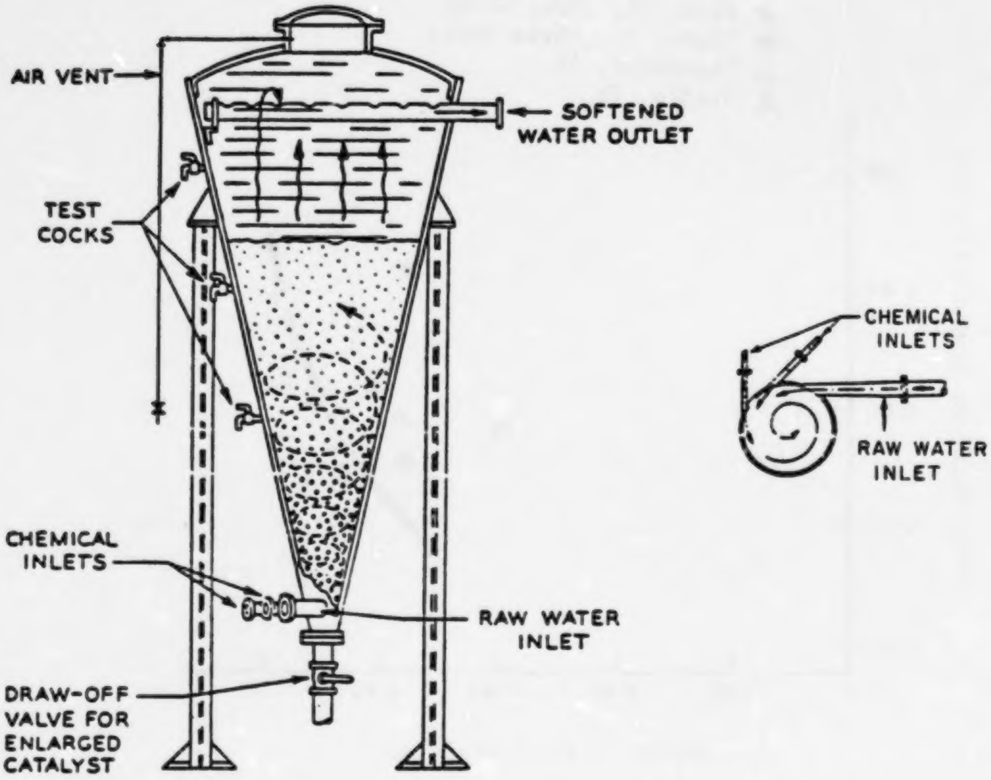
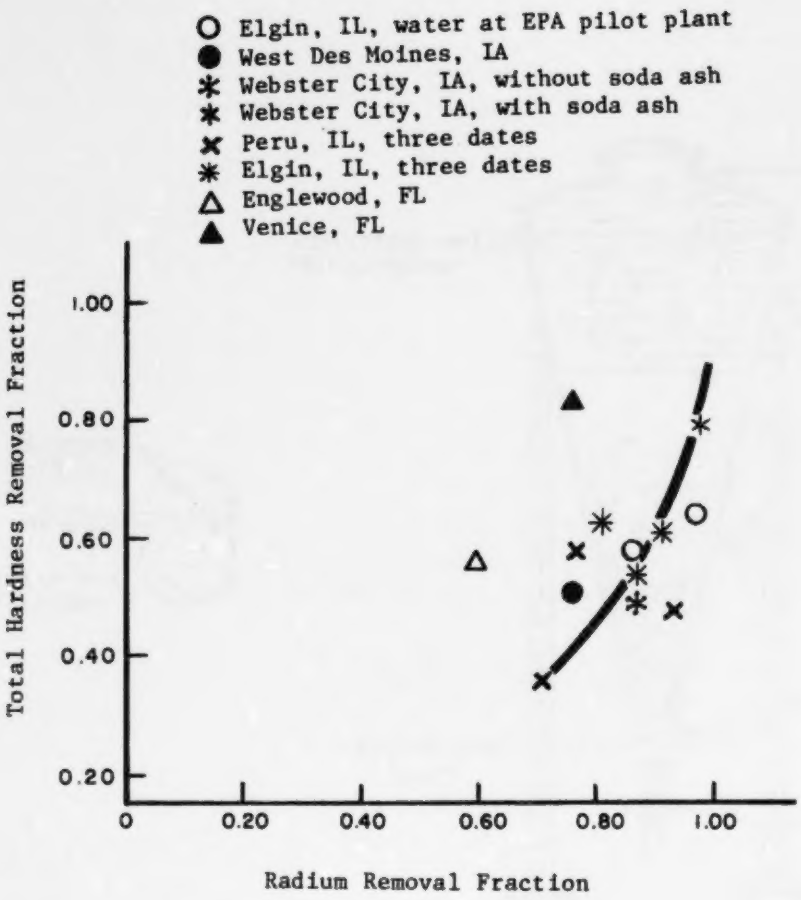
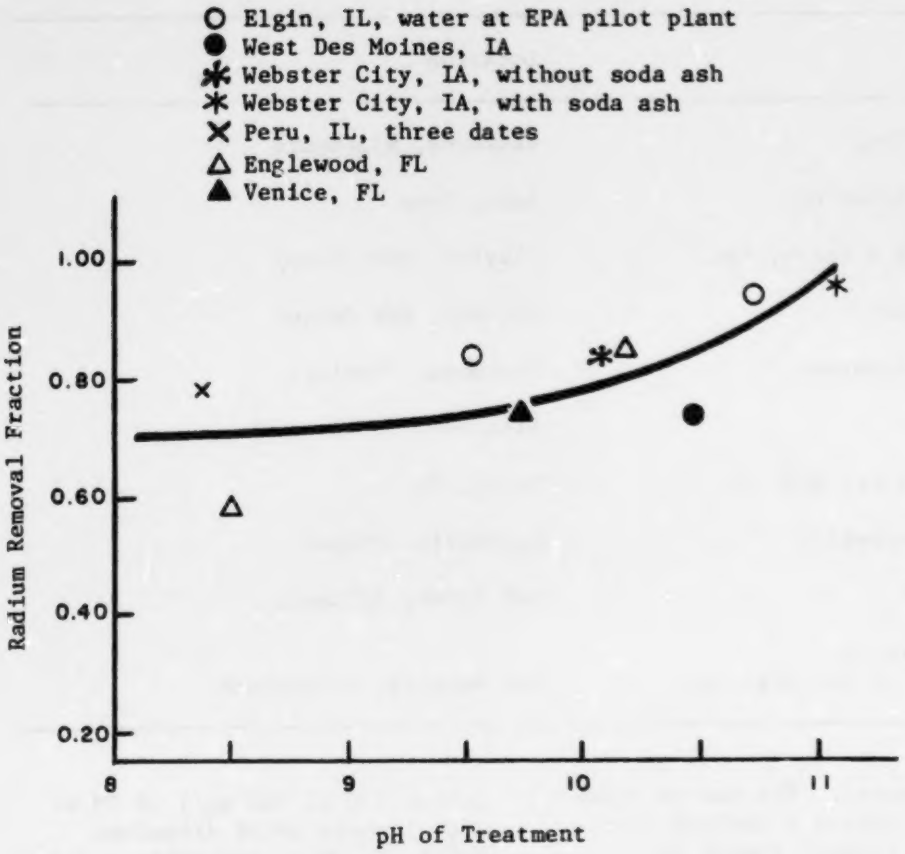

AIR VENT
SOFTENED WATER OUTLET
TEST COCKS
CHEMICAL INLETS
CHEMICAL INLETS
RAW WATER INLET
RAW WATER INLET
DRAW-OFF VALVE FOR ENLARGED CATALYST

Figure 3-3. Typical Upflow, Catalytic Lime Softening Unit



Source: EPA Publication 600/8-77-005, Manual of Treatment Techniques for Meeting the Interim Primary Drinking Water Regulations.

Figure 3-4. Lime-Soda Process, Total Hardness Removal Fraction Versus Radium Removal Fraction



Source: EPA Publication 600/8-77-005, Manual of Treatment Techniques for Meeting the Interim Primary Drinking Water Regulations.

Figure 3-5. Radium Removal Fraction Versus pH of Treatment, Lime-Soda Process

TABLE 3-2

LIME-SODA SOFTENING EQUIPMENT SUPPLIERS

Company	Location
Envirex, Inc.	Waukesha, Wisconsin
General Filter Co.	Ames, Iowa
Hungerford & Terry, Inc.	Clayton, New Jersey
Permutit Co.	Paramus, New Jersey
Infilco-Degremont	Richmond, Virginia
Dorr-Oliver	Stamford, Connecticut
Roberts Filter Mfg. Co.	Darby, PA
Neptune Microfloc	Corvallis, Oregon
Clow Corp.	Oak Brook, Illinois
Western Precip Division of Joy Mfg. Co.	Los Angeles, California

radium removal. The use of these curves to obtain a desired level of radium removal should be considered approximate, as considerable variation exists in the data used to derive the curves. This variation should pose no major problem during design, however, since hardness (and thus radium removal) can be easily regulated within previously stated limits by varying the amount of lime and/or soda ash added to the process units, which are sized based primarily on hydraulic considerations.

Lime or lime-soda softening is most applicable to waters of moderate to high total hardness (about 120 to 400 mg/l of TH as $CaCO_3$) where total dissolved solids is about 750 mg/l or less. When the raw water source is harder than about 400 mg/l, chemical requirements may be prohibitive. When TDS is about 750 mg/l, the finished water TDS may exceed the 500 mg/l secondary standard. Although it may be possible to reduce radium from a low hardness water using lime or lime-soda softening, site-specific data are not available and, therefore, such an application is not currently recommended.

Advantages and Disadvantages of Lime-Soda Softening for Radium Removal

The advantages of lime-soda softening are:

1. It produces an excellent quality water, and is easily capable of reducing radium to within the 5 pCi/1 MCL from source waters containing up to 25 pCi/1.
2. Finished water is easily stabilized to protect the distribution system.
3. Capital costs are competitive with ion exchange and reverse osmosis.
4. Trace metals, as well as radium, are removed in the process. In addition, the concentration of total dissolved solids is reduced and depending on initial alkalinity, no incease in sodium may be necessary.

The disadvantages of lime-soda softening are:

1. Operating costs are high, particularly chemical costs, as compared to ion exchange.
2. Requires significant operational attention.
3. Process is more difficult to control than ion exchange or reverse osmosis.
4. The process is currently limited, for reasons of practicality and equipment availability, to systems of 75,000 gpd or more.
5. The waste sludge may be difficult to dispose of.

Ion Exchange Treatment

Ion exchange treatment does exactly as the name implies: it trades one type of ion for another. The exchange process can be tailored to remove cations (positively-charged ions), by cation exchange, or to remove anions (negatively charged ions), by anion exchange.

Radium, present in water supplies as a cation is removed by the cation exchange process, which is also called ion exchange or zeolite softening. Uranium, probably present in water as an anion, has been shown in laboratory experiments to be removed by the anion exchange process. Both processes work by exchanging the ion of interest (radium, calcium, and magnesium cations; or uranium anions) with a similarly charged ion on the surface of a solid medium called an ion exchange resin. Both processes are reversible, which means the used resin can be regenerated and thus prepared for further exchange cycles. Except for the type of resin used, and perhaps the regenerant chemical, cation and anion exchange systems utilize the same equipment and operational procedures. Since considerable data are available on cation exchange systems for radium removal, and only very limited data on anion exchange systems for uranium removal exist, the discussion on ion exchange will focus primarily on cation exchange for radium removal. Anion exchange for uranium removal will also be addressed, but in a more limited fashion since its application to water treatment is currently still in the experimental stage.

Ion Exchange Softening (Cation-Exchange)

In the ion-exchange softening process, the hardness causing calcium and magnesium cations are removed by exchange with a cation such as sodium or hydrogen which does not impart hardness to a water. This exchange takes place on the surface of the ion exchange resin through which the water is passed. Radium, being a divalent cation (+2 electrical charge) similar to calcium and magnesium, is also removed from water by ion exchange softening.

Ion exchange is a reversible process. Once the exchange resin is exhausted (can remove no more hardness ions), it can be regenerated by soaking the resin in a strong solution of sodium chloride (salt), which returns the resin to its original condition, ready for further cycles.

An acid solution may also be used as a regenerant if it is desirable to limit the amount of sodium added to the raw water in the exchange process. If an acid regenerant is used, the system is said to be operating in the hydrogen cycle. When salt is used as the regenerant, the system is said to be operating in the sodium cycle. Although hydrogen cycle operation, due to the requirements for handling and disposing of relatively concentrated acid streams, has been unpopular for application by small water utilities, its use may be desirable to eliminate the addition of sodium in certain systems.

Originally, media used for ion exchange softening came from natural sources such as greensand (glauconite) found in various parts of the world; the largest principal commercial deposit being in New Jersey. The term "zeolite" has been loosely applied to all those materials which are used for ion exchange softening, including greensand, bentonitic clay, synthetic gel-type material, sulfonated coal, and the synthetic organic resins. Strictly speaking, the term zeolite should include only those organic aluminosilicates which display ion exchange properties.

Most of the ion exchange resin used today, cationic and anionic, are manufactured materials which are resistant to attack over a wide pH range and are physically strong enough that they do not break up during use. Ion exchange resins are tiny spherical beads about the size of medium sand. The beads are uniform in size and color. Each bead is, in effect, a skeleton on which numerous exchange sites are available. A partial list of the manufacturers of ion exchange resin are listed in Table 3-3.

How Ion Exchange Softening Works

Figure 3-6 is a schematic of a typical ion-exchange system. An ion-exchange cycle consists of: softening - exhaustion - regeneration - backwash. When an ion exchanger is placed in service, either initially or following regeneration, sodium ions are present on the exchange resin. As hard water is passed through the exchanger, the hardness-causing ions, including radium, are replaced in the water by the sodium ions from the resin and the hardness-causing ions replace the sodium ions on the resin. A

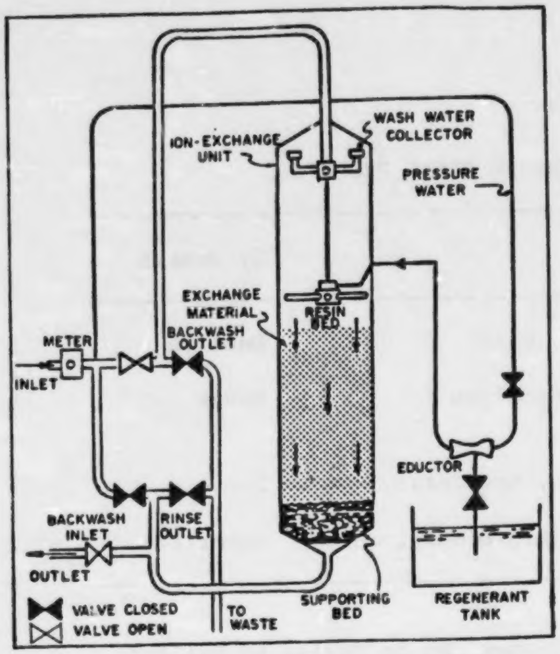

ION-EXCHANGE UNIT
WASH WATER COLLECTOR
PRESSURE WATER
EXCHANGE MATERIAL
RESIN BED
METER
BACKWASH OUTLET
INLET
EDUCTOR
BACKWASH INLET
RINSE OUTLET
OUTLET
VALVE CLOSED
VALVE OPEN
TO WASTE
SUPPORTING BED
REGENERANT TANK

Figure 3-6a. Diagram of Typical Ion-Exchange Unit - Softening Mode

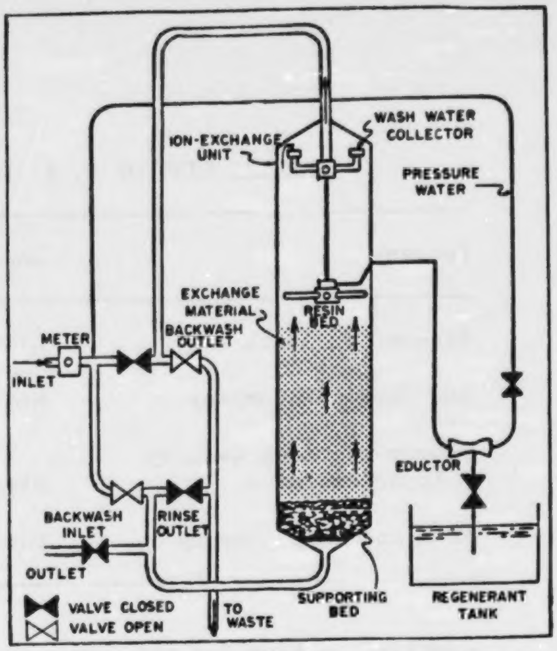

ION-EXCHANGE UNIT
WASH WATER COLLECTOR
PRESSURE WATER
EXCHANGE MATERIAL
RESIN BED
METER
BACKWASH OUTLET
INLET
EDUCTOR
BACKWASH INLET
RINSE OUTLET
OUTLET
VALVE CLOSED
VALVE OPEN
TO WASTE
SUPPORTING BED
REGENERANT TANK

Figure 3-6c. Diagram of Typical Ion-Exchange Unit - Backwash Mode

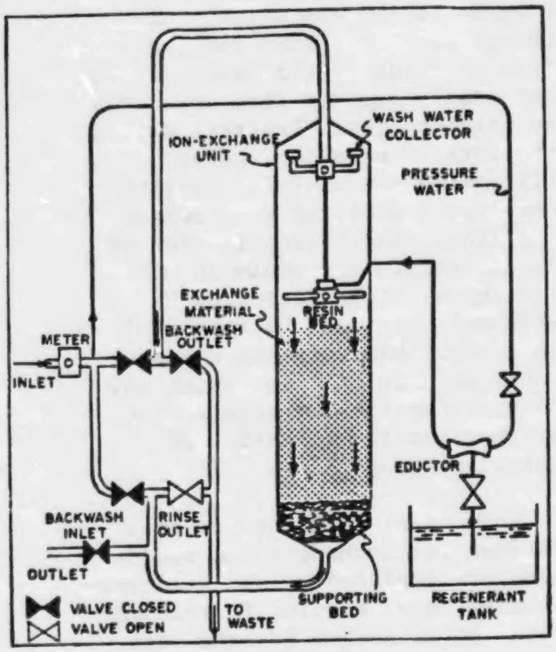

ION-EXCHANGE UNIT
WASH WATER COLLECTOR
PRESSURE WATER
EXCHANGE MATERIAL
RESIN BED
METER
BACKWASH OUTLET
INLET
EDUCTOR
BACKWASH INLET
RINSE OUTLET
OUTLET
VALVE CLOSED
VALVE OPEN
TO WASTE
SUPPORTING BED
REGENERANT TANK

Figure 3-6b. Diagram of Typical Ion-Exchange Unit - Regeneration Mode

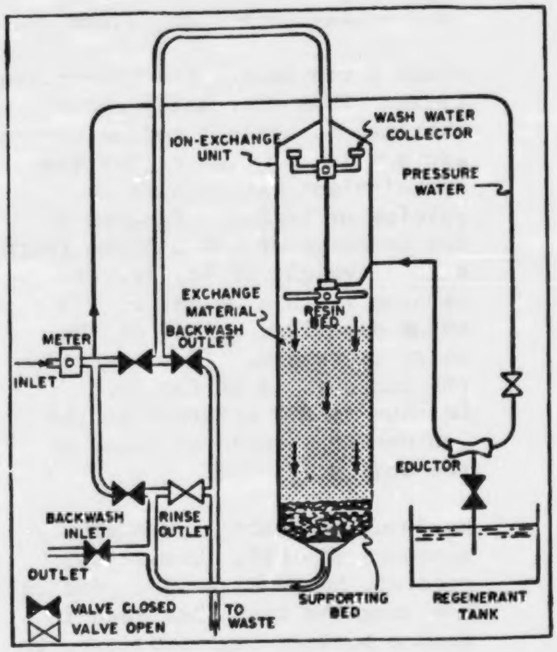

ION-EXCHANGE UNIT
WASH WATER COLLECTOR
PRESSURE WATER
EXCHANGE MATERIAL
RESIN BED
METER
BACKWASH OUTLET
INLET
EDUCTOR
BACKWASH INLET
RINSE OUTLET
OUTLET
VALVE CLOSED
VALVE OPEN
TO WASTE
SUPPORTING BED
REGENERANT TANK

Figure 3-6d. Diagram of Typical Ion-Exchange Unit - Rinse Mode

Figure 3-6. Operation Modes in a Typical Ion-Exchange Unit

TABLE 3-3

PARTIAL LIST OF U. S. ION EXCHANGE RESIN PRODUCERS

Company	Location	Trademark
Diamond Shammock	Cleveland, Ohio	Duolite
Dow Chemical Company	Midland, Michigan	Dowex
Sybron Chemical Company Ionac Division	Birmingham, New Jersey	Ionac
Rohm and Haas Company	Philadelphia, Pennsylvania	Amberlite

general equation for the ion-exchange softening process step is:

Softening

$$Ca^{++} + 2NaR \longrightarrow CaR_2 + 2Na^+$$

where R represents the ion-exchange resin. This expression shows that two monovalent sodium cations are now in solution rather than one divalent cation such as calcium or radium. Because of the exchange of two sodiums (with a total weight of 46) for one calcium (with a weight of 40) the total dissolved solids of the water increases. (For magnesium the exchange is 46 for 24.) Calcium is now attached to the ion exchange resin in place of two sodiums.

Hardness and radium removal may approach 95-100%. The actual removal, however, will depend on how long the resin has been in sevice between regenerations, the surface loading rate, the contact time of water with the resin, and the condition of the resin.

Resins can be fouled by buildup of suspended solids not removed during backwashing, by biological growth in the resin bed, and by concentrations of iron (2 to 3 mg/l) in the raw water. Although iron is easily removed from solution by the resin, it is not easily removed from the resin by regeneration. Pretreatment in the form of aeration and/or filtration can minimize fouling problems associated with solids and iron. The preapplication of disinfectants can minimize bed fouling by biological growth, although care must be taken not to indiscriminately use disinfectants such as chlorine which may damage some ion-exchange resins, or increase the formation of total trihalomethanes.

As hard water continues to pass through the exchanger and sodium ions are replaced by the hardness-causing ions, a point is reached when the exchanger is exhausted. Exhaustion means that the amount of hardness-causing ions exchanged for sodium has decreased beyond an acceptable point and the effluent is "harder" than desired. This is also sometimes called "break-through."

Fortunately for the waterplant operator, radium is held on the resin after the resin bed has been exhausted for hardness removal. This occurs because when the bed is saturated with calcium or magnesium ions, most cation-exchange resins will preferrentially exchange a radium ion for a calcium or magnesium ion. Thus, a water plant operator can safely operate an ion-exchange softener until hardness "breaks through" the bed before regeneration, and any radium in the raw water will continue to be removed by the resin. This removal of radium following hardness exhaustion will not continue indefinitely, however. Once hardness break-through has occurred, the operator should start the regeneration step of the resin bed as soon as possible. Regeneration of an ion-exchange softener means replacing the hardness-causing ions on the resin with sodium ions, such as shown by the following reaction:

Regeneration

$$CaR_2 + 2Na^+ \longrightarrow Ca^{++} + 2NaR$$

The regeneration step differs from the softening step in that the concentration of sodium ions in the regenerant is many times greater than the concentration of hardness-causing ions present in the untreated water. Therefore, the volume of regenerant solution, such as a concentrated salt solution or brine, is only a fraction of the total water volume processed in the softening step. As a result, the concentration of the hardness-causing ions is many times greater in the waste regenerant than in the untreated water.

As shown in Figure 3-6, highly concentrated regenerant (salt) from a storage tank is diluted with untreated water to the concentration recommended by the resin manufacturer. The diluted regenerant is then pumped through the resin bed in the same direction as was the water during the softening step. This is done for two reasons: 1) the more exhausted resin is at the top of the bed where contact is first made with the untreated water, and 2) the regenerant solution can drain from the resin bed reducing the volume of backwash water needed to flush the bed. A lateral type distributor is used to spread regenerant over the resin surface.

The volume of regenerant solution needed will depend on the specific resin, concentration of regenerant solution and the volume of ion-exchange resin. Generally, manufacturers will specify the pounds of sodium chloride to be used per cubic foot of resin. Typically, a 10 percent brine solution is used as the diluted regenerant. The regeneration cycle time will depend on the volume of regenerant required and the loading rate specified by the manufacturer.

Following regeneration, the excess brine and solids entrapped in the resin bed must be flushed out. This is accomplished during backwash of the resin bed. During backwash, treated water is applied in an upflow direction at a rate sufficient to gently separate the individual resin beads. This expansion allows suspended materials to be flushed from the bed and prepares the bed for further operation by minimizing "channeling" or inconsistent flow through the bed during operation.

The length of the backwash cycle is specified by the manufacturer, but may be changed, if necessary. In most cases, this will depend more on requirements for solids removal than on flushing of the brine.

Once the backwash cycle is complete, the ion-exchange column can be placed back into service beginning the softening process again, and therefore removal of radionuclides. With experience, the ion-exchange operating cycle can be placed on a time sequence. That is, the length of time between regenerations, the regeneration cycle time and the backwash cycle length can all be pre-set based on historical performance. Occasional adjustment of the time cycle may be required as the resin ages or if the raw water quality changes.

The waste regenerant brine and the backwash water both require disposal. The waste brine is a disposal problem due more to its brine content than to the small amount of radium it contains. Disposal options and requirements are discussed in Section V.

Ion Exchange Equipment

An ion-exchange treatment unit consists of a tank or vessel which contains the ion-exchange resin, along with associated valves, pumps, piping, and controls. A storage tank for regenerant salt and a vessel for mixing of regenerant brine solutions are also part of a complete treatment unit.

The treatment vessel may be the pressure-type device or the open gravity type. Most small treatment systems use a pressure-type vessel similar to the one depicted in Figure 3-7. A typical pressure unit generally consists of a closed steel cylinder which may be placed vertically or horizontally. In designing such tanks the diameter must be limited to less than 12 feet because of overland shipping restrictions. Gravity or open top softeners usually are built of concrete and are rectangular in shape, although some round steel gravity units have been built. The pressure-type has one advantage over the open-type in that it is possible to pump water to the unit directly from the source of supply, through the unit and directly into the distribution system without repumping. Gravity filters also have advantages. Since they are open top, it is possible to see what is happening inside and, therefore, identify any problems such as channeling. Also, during the backwash cycle, loss of resin can be seen and corrected.

Suppliers of Ion-Exchange Systems

There are many suppliers of ion-exchange equipment packages. Table 3-4 is a partial list of these manufacturers.

Most of these manufacturers provide package systems or components within the size range of the small water supply. Most also provide bench scale testing and full design capabilities.

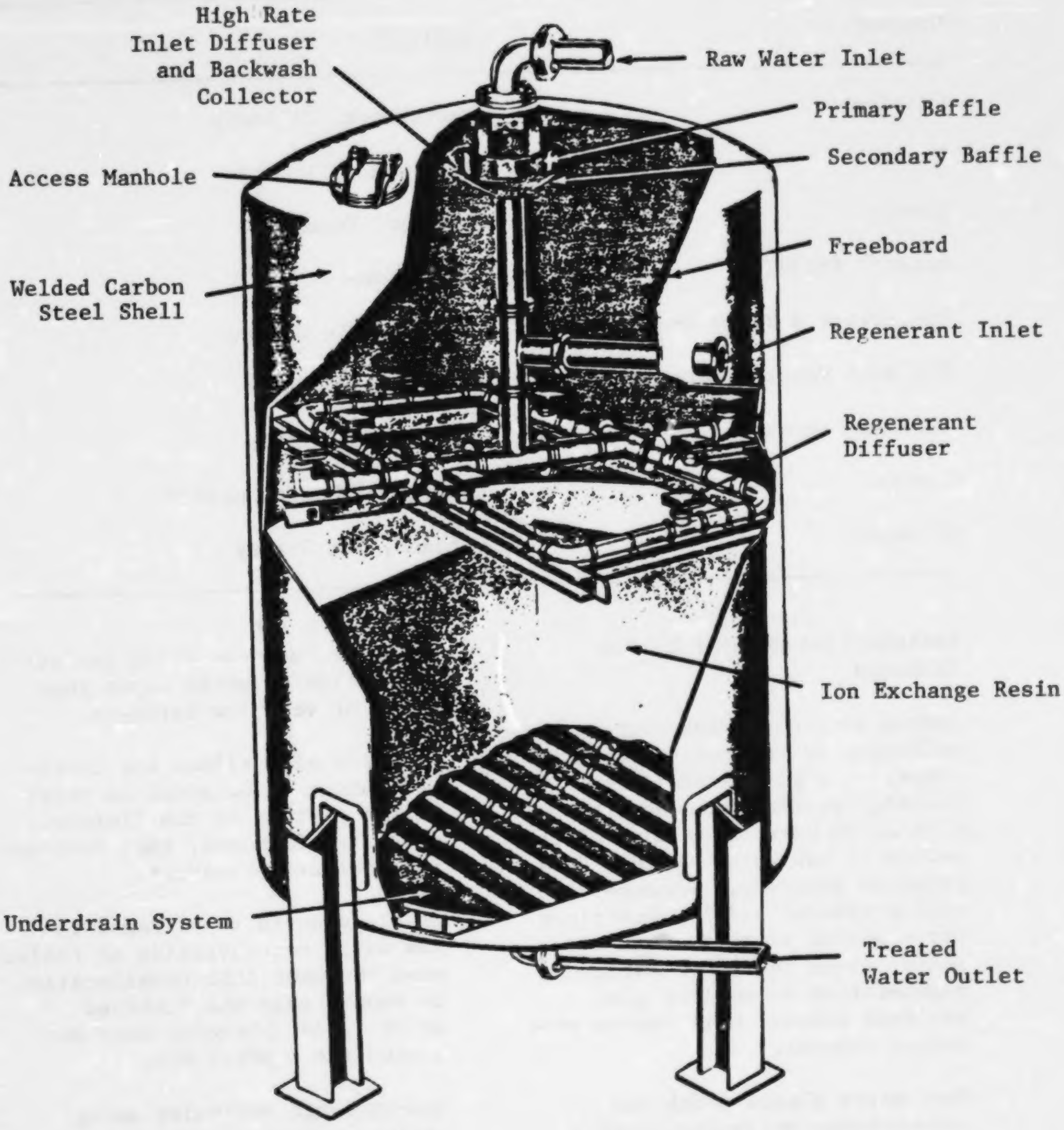

High Rate
Inlet Diffuser
and Backwash
Collector
Raw Water Inlet
Primary Baffle
Secondary Baffle
Access Manhole
Freeboard
Welded Carbon
Steel Shell
Regenerant Inlet
Regenerant
Diffuser
Ion Exchange Resin
Underdrain System
Treated
Water Outlet

Figure 3-7. Typical Pressure-Type Ion Exchange Treatment Vessel

TABLE 3-4

PARTIAL LIST OF U. S. SUPPLIERS OF ION EXCHANGE SYSTEMS

Company	Location
Culligan	Northbrook, Illinois
Envirex	Waukesha, Wisconsin
Graver	Houston, Texas
General Filter	Ames, Iowa
Hungerford & Terry Inc.	Clayton, New Jersey
Illinois Water Treatment	Rockford, Illinois
Infilco-Degremont	Richmond, Virginia
Ionics	Watertown, Massachusetts
Permutit	Paramus, New Jersey

Radionuclide Removal by Ion Exchange

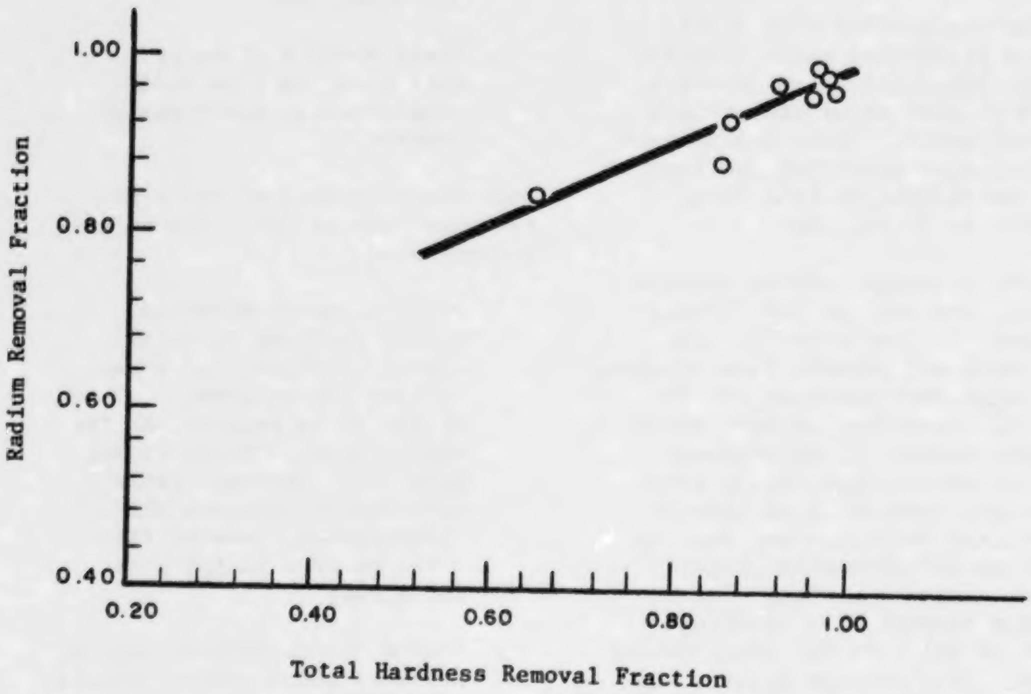
Radium removal by ion-exchange softening is related to hardness removal. Well-operated ion-exchange plants can remove as much as 95 percent or more of the radium in raw water (Figure 3-8) prior to blending. Because radium removal still takes place for a period of time after the resin ceases to remove hardness, regeneration to achieve good hardness removal will assure good radium removal.

Most water plants which use ion-exchange softening blend a portion of the raw water with the treated (nearly zero hardness) water. This is done in order to produce a finished water of moderate hardness which is less corrossive to water pipes than water of very low hardness.

Blending also allows the treatment units to be sized to treat only a portion of the finished water requirements, thus increasing cost effectiveness.

If blending is to be done, the raw water concentration of radium must be taken into consideration to ensure that the finished water, after blending does not exceed the 5 pCi/1 MCL.

Ion-exchange softening using cation exchange resins is not effective in removing uranium from drinking water, since uranium is present in most water sources primarily as an anion



Source: Manual of Treatment Techniques for Meeting the Interim Primary Drinking Water Regulations, EPA 600/8-77-005, May 1977.

Figure 3-8. Radium Removal Fraction Versus Total Hardness Removal Fraction in Ion Exchange Plants, Before Blending

(uranyl carbonate). Anion exchange resins should be very effective for selective uranium removal. Mixed bed ion exchangers (with cation and anion exchange resins) have been used successfully in some ion-exchange applications. Their potential for radionuclide removal is uncertain and should be evaluated on a case-by-case basis.

Laboratory studies have shown that a particular anion exchange resin, Dowex 1-X2, can remove up to 99 percent of uranium from a natural water. These preliminary studies also show that the resin has the ability to hold large quantities of uranium.

Anionic exchange systems operate exactly the same as ion exchange softeners. They have the same equipment and process flow schemes. The regenerant solution and the type of resin are the only major changes required. No hardness removal would occur during anion exchange; however, some removal of natural water anions, such as sulfates or carbonates, might occur. Anionic exchange for uranium removal from drinking water is still in the experimental stage. Considerable pilot-scale testing would be required before a utility could use such a system.

Advantages and Disadvantages of Ion-Exchange Sofening for Radionuclide Removal

The advantages of ion-exchange softening for radionuclide removal are:

1. Ease of operation and control; many ion-exchange plants are completely automated, reducing need for labor;
2. Finished water hardness and radionuclide content can be closely controlled by blending treated water with raw water in varying amounts;
3. Costs can be held quite low for small plants;
4. Treated water alkalinity is not affected by sodium cycle operation; and
5. Trace amounts of heavy metals, as well as radionuclides, are often easily removed.

Some disadvantages of the ion-exchange process for radionuclide removal are:

1. Finished water shows an actual increase in total dissolved solids since one calcium ion of atomic weight 40 is replaced by two sodium ions of total atomic weight 46; Hydrogen cycle operation eliminates this disadvantage, however finished water alkalinity is decreased;
2. Sodium concentrations may be elevated above concentrations allowed for people on sodium restricted diets. In addition, elevated sodium levels may be associated with increased incidence of hypertension and cardiovascular diseases. Hydrogen cycle operation eliminates this disadvantage, however finished water alkalinity is decreased and operational control is more difficult;
3. Raw water requires pretreatment if turbidity and suspended solids, iron and manganese, or bacterial slimes are present;

4. Finished water may be corrosive in distribution lines unless some form of stabilization is practiced;

5. Disposal of spent brines can be a difficult problem. Regulatory agency approval is often difficult to obtain. Brine disposal is discussed in more detail in Section V.

Reverse Osmosis

Reverse osmosis (RO) is a membrane treatment process capable of demineralizing water. Water which has passed through an RO membrane is low in inorganic and organic constituents, essentially free of suspended matter, bacteria and virus. Radium, uranium, and most manmade radionuclides can be removed by RO. Radium and uranium removals by RO systems generally exceed 95 percent.

Because RO is generally an expensive treatment technique, it is usually applied for treatment of brackish water or sea water.

Process Description

Osmosis is a property of solutions defined as the spontaneous flow of water into a solution. When both diluted and concentrated solutions are separated by a porous membrane, osmosis occurs as the dilute solution passes through the membrane into the concentrated solution (Figure 3-9a). If the membrane which separates the solutions is selective in that the solvent (pure water) can pass through the membrane while dissolved material in the solution cannot, the membrane is said to be "semipermeable." The osmotic pressure is that pressure which must be used to prevent the passage of pure water through a membrane which separates the solution and the water.

By applying pressure greater than the osmotic pressure to the more concentrated solution of a semipermeable membrane, pure water can pass through the membrane while the dissolved materials cannot (Figure 3-9b). This process, known as reverse osmosis, is very effective in separating divalent or trivalent ions, including the radionuclides radium and uranium, from water. RO processes are governed by two basic principles, the flow of water through the membrane depends on the pressure applied and the movement of the dissolved material is dependent upon the concentration differences in the feed water and product water.

The difference between the applied pressure and the osmotic pressure of the solution determines the flow of water through the membrane. The difference in concentration between the feed water and the product water determines the rate of ion movement toward the membrane. These factors vary for different membranes and the way they are placed in RO modules.

Types of Membrane Systems

There are two major membrane configurations: the spiral-wound module (Figure 3-10) and the hollow fiber (Figure 3-11). The spiral-wound membrane has one or more membrane envelopes each with a porous material between two large, flat membrane sheets. The membrane envelope is sealed on three edges with a special ad-

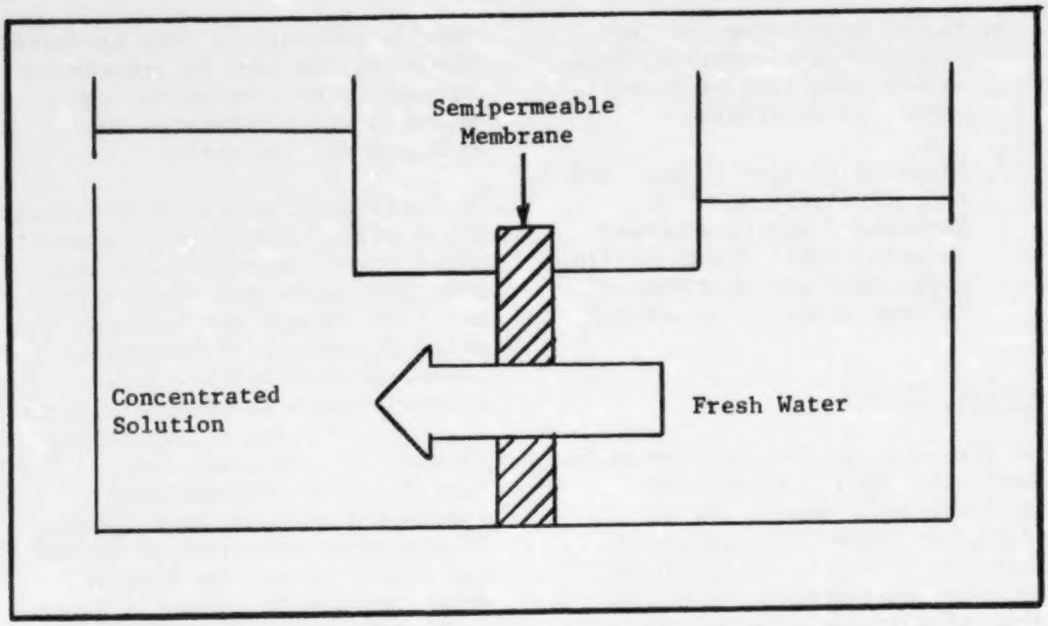
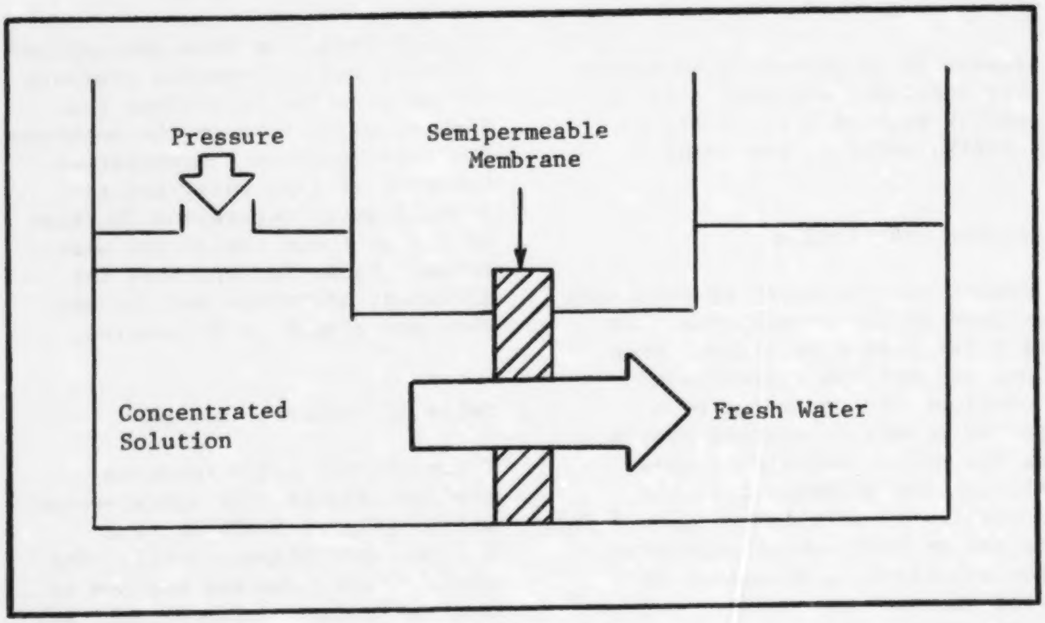
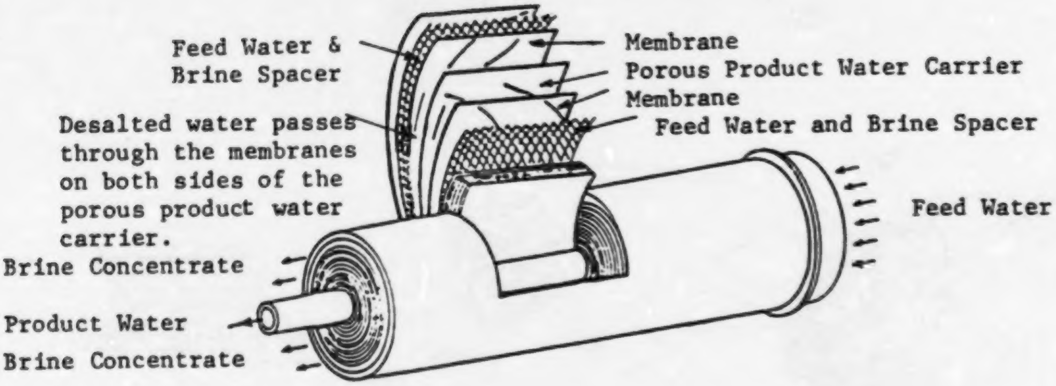

Semipermeable
Membrane
Concentrated
Solution
Fresh Water

Figure 3-9a. Osmosis - Normal Flow from Low-Concentration Solution to High-Concentration Solution


Pressure
Semipermeable
Membrane
Concentrated
Solution
Fresh Water

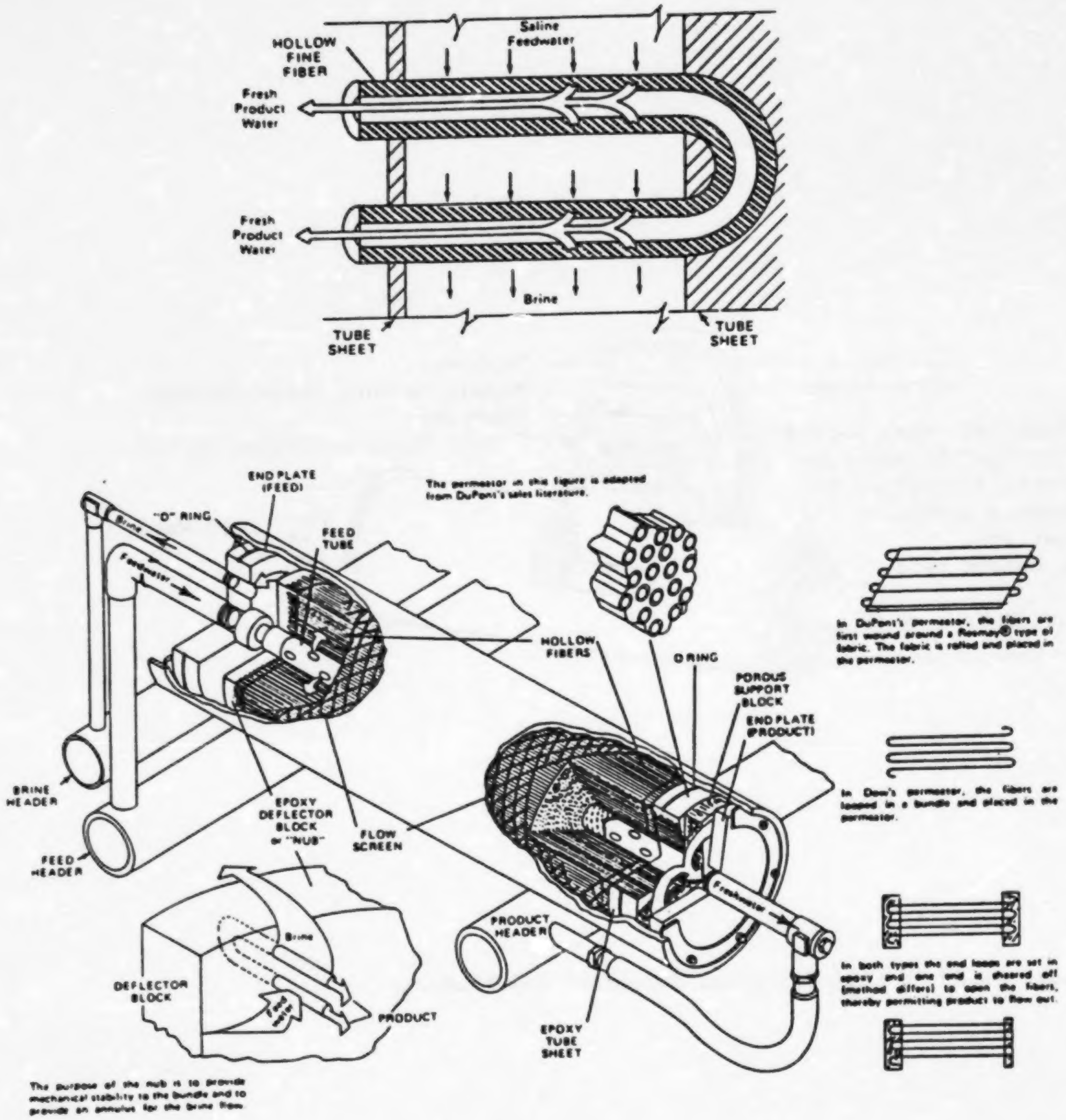
Source: Costs of Radium Removal From Potable Water Supplies, MERL, Cincinnati, OH, EPA-600/2-77-073.

Figure 3-9b. Reverse Osmosis - Flow Reversed by Application of Pressure to High-Concentration Solution


Feed Water &
Brine Spacer
Membrane
Porous Product Water Carrier
Membrane
Feed Water and Brine Spacer
Desalted water passes through the membranes on both sides of the porous product water carrier.
Feed Water
Brine Concentrate
Product Water
Brine Concentrate

Source: Fluid Systems Division, Universal Oil Products

Figure 3-10. Cutaway View of a Spiral Membrane Element


HOLLOW FINE FIBER
Saline Feedwater
Fresh Product Water
Fresh Product Water
Brine
TUBE SHEET
TUBE SHEET
END PLATE (FEED)
"O" RING
FEED TUBE
Brine
Feedwater
HOLLOW FIBERS
O RING
POROUS SUPPORT BLOCK
END PLATE (PRODUCT)
BRINE HEADER
FEED HEADER
EPOXY DEFLECTOR BLOCK or "NUB"
FLOW SCREEN
PRODUCT HEADER
Feedwater
DEFLECTOR BLOCK
Brine
PRODUCT
EPOXY TUBE SHEET

The permeator in this figure is adapted from DuPont's sales literature.

In DuPont's permeator, the fibers are first wound around a Reemay® type of fabric. The fabric is rolled and placed in the permeator.

In Dow's permeator, the fibers are looped in a bundle and placed in the permeator.

In both types the end loops are set in epoxy and one end is sheared off (method differs) to open the fibers, thereby permitting product to flow out.

The purpose of the nub is to provide mechanical stability to the bundle and to provide an annulus for the brine flow.

Figure 3-11. Permeator Assembly for Hollow Fine Fiber Membranes

hesive and attached with the adhesive to the outside of a small diameter pipe. The pipe has openings to collect the water which passes through the membrane. This product water is referred to as the permeate. The envelopes are wound around the pipe to form a cylinder with diameters ranging from 2 to 12 inches and up to 40 inches in length. The envelope is wrapped on the outside to prevent bursting. The inner pipe allows for the flow of permeate and for the connection of several sections of membrane elements. The entire series of membrane elements are then housed within a pressure vessel.

The second type of RO membrane design is the hollow, fine fiber membrane, which uses either a polyamide polymer membrane made by DuPont or a cellulose triacetate membrane made by Dow Chemical Company. The polyamide fibers have diameters between 50 to 85 microns (10^{-4} centimeters) with the internal diameter of the hollow fiber about one-half the outer diameter. The cellulose triacetate fibers have outer diameters of 200 to 300 microns. The membrane and pressure vessel as shown in Figure 3-11 are integrated units. The fibers are formed into a V-shaped bundle, with the open ends in an epoxy tube sheet. The bundle attached to the tube sheet is arranged in a cylindrical pressure vessel.

In the hollow fiber membrane system, feedwater is pumped to the center of the vessel through perforated pipe. Under pressure the water is forced through the hollow fibers and the permeate flows out through the middle of the fibers. The water and dissolved solids which do not pass through the fibers continues through the bundle and flows through a discharge pipe. This part is referred to as the "reject" stream.

Both systems require large high pressure pumps to produce pressures greater than the osmotic solution pressure and to maintain continuous flow of permeate. The hollow fiber design is simple to install, but clogs more easily than a spiral wound design. With either membrane design, an RO system is built of one or more modules. The modules can be connected in parallel with each module receiving part of the total flow not previously treated by RO, or in series with the permeate from one or more RO modules becoming the feed to the next module in the series. Series operation is used when high removals of a contaminant are required.

Figure 3-12 depicts a simplified schematic of a typical RO system.

Pretreatment Requirements

As with any equipment, operation of an RO system is not problem free, but with proper pretreatment before the membrane, better and more continuous performance may be maintained. Scaling of the membrane can be caused by the precipitation of slighlty soluble compounds. As the feed water passes through the system, the reject portion will become more concentrated in these slightly soluble compounds, which will precipitate on the membrane. Calcium carbonate (CaCO) is the most common substance that precipitates. It can be controlled by reducing the pH and by the addi-

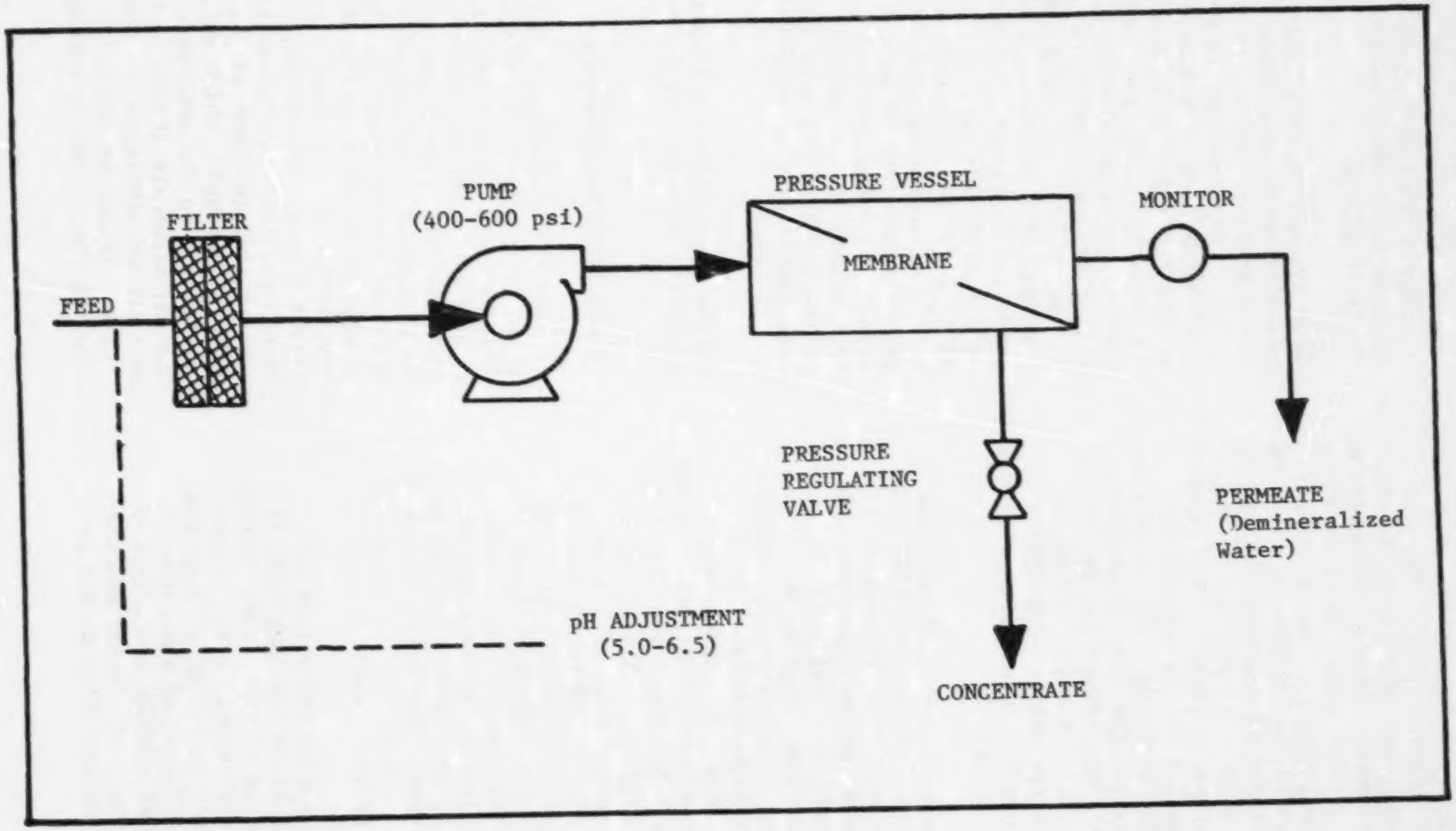

PUMP
(400-600 psi)
PRESSURE VESSEL
MONITOR
FILTER
MEMBRANE
FEED
PRESSURE
REGULATING
VALVE
PERMEATE
(Demineralized
Water)
pH ADJUSTMENT
(5.0-6.5)
CONCENTRATE

Figure 3-12. Typical Reverse Osmosis System

tion of substances that tie up the calcium. In waters with high sulfate concentrations, calcium sulfate, barium sulfate, and strontium sulfate may also foul the membrane. Calcium fluoride has also been found to be a problem. In most cases hexametaphosphate may be added to tie up the calcium and prevent precipitation on the membrane.

Suspended matter can cause plugging of the membrane, thus reducing the flow of water through the membrane. Generally, suspended solids in the feed water are reduced by a 5 to 10 micron filter ahead of the membrane. A measure of this type of interference is the Silt Density Index (SDI). SDI is measured by passing the raw water through a 0.45-micron filter at a pressure above 30 pounds per square inch gage (psig). The time (seconds) required to collect 500 milliliters (ml) is recorded. After an elapsed time of 5 minutes, fresh water is again passed through the same filter and the time to collect 500 mls is recorded. This procedure is repeated again after total elapsed times of 10 and 15 minutes.

The SDI is

$$SDI = P_{30} \frac{(1-ti/tf)\ (100)}{T}$$

where T is the total test duration (seconds), P_{30} is the percent pluggage at 30 psig pressure, ti is the initial time (seconds) required to obtain the first 500 ml sample, and tf is the time (seconds) required to obtain respective samples after elapsed times of 5, 10 and 15 minutes. The SDI is calculated for each time interval. Most waters have an SDI value less than 3. Reverse osmosis cannot be used on waters wth an SDI greater than 6.

Iron and manganese oxides can also cause fouling of membranes. Iron concentrations in the raw waters should be less than 5 mg/l if no oxygen is present, and less than 0.05 mg/l if the dissolved oxygen concentration is 5 mg/l or above. In cases where iron or manganese concentrations are greater than recommended for RO use, some form of iron and manganese removal such as aeration followed by settling or filtration may be necessary.

Because of the number of materials which can foul an RO membrane and deterioration of the membrane material with time, design of RO systems are normally conservative so that the system can provide desired treatment over the lifetime of the membrane. In the design example in Section IV, this approch is discussed more fully.

Other Factors Influencing Operation

Other factors which affect RO performance include bacteria which may accumulate on the membrane and cause fouling. Some bacteria have been found to attack the membrane. Temperature also affects performance, which is generally improved as temperature increases; however, if water temperature is above that recommended by the manufacturer, the performance will be decreased. This will depend on the type of membrane materials. Finally, chlorine will also attack certain membrane materials, expecially the aromatic polyamide manufactured by DuPont.

Since RO concentrates the solids in the reject stream, this stream will be much more concentrated in dissolved materials, including salts and radionuclides, than the feed water and disposal may be a difficult problem. The salinity of the reject stream is generally of more environmental concern than its radionuclide content. Section V addresses disposal options and regulatory concerns.

The permeate contains carbon dioxide as a result of the low pH. Carbon dioxide can be removed easily in post treatment by aeration in a forced draft aerator called a "decarbonator."

Suppliers of Reverse Osmosis System

Table 3-5 is a partial list of U.S. reverse osmosis equipment manufacturers and suppliers. Most of these manufacturers provide RO modules for any size range including point-of-use. Most will also provide design and analytical services to assist in the selection and design of RO systems, including requirements for pre- and post-treatment equipment.

Radionuclide Removal by Reverse Osmosis

Reverse osmosis will remove about 95 percent of radium and uranium in the feed water of a single pass system. The removal of the radionuclide is not directly affected by the removal of any other particular substance, including hardness; unlike the lime-soda and ion exchange softening processes. The degree of removal by an RO system is called the rejection rate. It is determined by the membrane material, module design as well as operating conditions such as pressure, and the quality of the feedwater. An advantage of reverse osmosis is its high rate of rejection of all dissolved solids in the feedwater. This rejection rate allows brackish and sea water to be desalted for potable use. It also allows RO to be used to treat water for man-made radionuclide removal. Permeate from an RO system will be very low in hardness and free from many other organic and inorganic contaminants.

Advantages and Disadvantages of Reverse Osmosis for Radionuclide Removal

The advantage of reverse osmosis for radionuclide removal are:

1. High rate of rejection of nearly all dissolved solids in raw water, including radium, uranium and many man-made radionculides.
2. Only process that can be used on brackish or saline waters (as compared to ion-exchange or lime-softening).
3. Process control is relatively simple.

The disadvantages of reverse osmosis for radionuclide removal are:

1. High capital and operating costs.
2. Considerable pretreatment requirements, particularly if raw water contains suspended solids, organic material, or dissolved gases.

TABLE 3-5

PARTIAL LIST OF REVERSE OSMOSIS SYSTEM SUPPLIERS

Company	Location
Basic Technologies	Riviera Beach, Florida
Envirogenics	El Monte, California
Fluid Systems Division, UOP, Inc.	San Diego, California
DuPont	Wilmington, Delaware
Dow Chemical Company	Midland, Michigan
Infilco-Degremont, Inc.	Richmond, Virginia
Neptune Microfloc	Corvallis, Oregon
Permutit Company	Paramus, New Jersey

3. Reject stream requires disposal. The relatively high volume of this stream, 25 to 50 percent of treated water volume, adds to disposal problem.

4. Finished water must be stabilized with lime or other chemicals to prevent corrosion in distribution system.

IV. DESIGNING A REMOVAL SYSTEM FOR NATURALLY OCCURRING RADIONCULIDES

INTRODUCTION

This section includes a discussion of the factors considered in the selection and design of a removal system for naturally occurring radionuclides (uranium and radium). Any reference to radionuclides in this section implies only uranium or radium. The section is organized to:

1. Present general considerations and information necessary in selection and design of a radionuclide removal system,
2. Present a discussion of factors affecting the selection of an appropriate treatment system, and
3. Show how to design a radionuclide treatment system (lime-soda softening, ion exchange, or reverse osmosis).

This section also provides enough information to familiarize the designer with basic design considerations and terminology for each of the three treatment systems considered as they relate to radionuclide removal.

CONSIDERATIONS IN THE DESIGN OF A RADIONUCLIDE TREATMENT SYSTEM

In the design of a radionuclide removal system, as well as for most of the water treatment processes, the actual system design is specific to the location, raw water characteristics, and consumptive water demands. Depending upon the raw water characteristics and type of treatment process selected for radionuclide removal, various pretreatment and/or posttreatment operations are required. The need for pretreatment may result from reduced performance caused by materials contained in the raw water. For example, iron and manganese oxides can foul the membrane of the reverse osmosis (RO) process limiting the flow of water. Removing these oxides or preventing their formation prior to the RO system through pretreatment will then permit unhampered use of the RO process for removal of the radionuclide. Posttreatment may often be necessary to adjust the water quality following treatment for radionculide removal to ensure that the water meets all drinking water standards, including radionuclides, or to make the water more palatable or less corrosive. As with pretreatment, the type of posttreatment will depend on raw water characteristics and the radionuclide treatment method selected.

If the available nontreatment alternatives (refer to Section III for discussion) will not solve the problem, or if a comparison of nontreatment with treatment alternatives is required before a decision can be made, then the following factors must be considered:

- Raw water quality;
- Finished water quality requirements;
- Treatment capability of candidate system;
- Pretreatment/posttreatment requirements for each candidate system;

- Regulatory requirements, including disposal of sludges generated or reject process streams;
- Site-specific limitations;
- Costs, including energy;
- Materials of construction; and
- Availability of trained operating and maintenance personnel.

Three treatment processes capable of removing radium were discussed in Section III; lime-soda softening, ion exchange, and reverse osmosis. As discussed, ion exchange and reverse osmosis will also remove uranium but for ion exchange to be effective, an anionic resin will be necessary.

RADIONUCLIDE REMOVAL DESIGN CHECKLIST

The initial step in the design of any treatment process is extensive information gathering. After the problem is identified, all information necessary to complete the design, estimate costs, and make purchasing decisions must be compiled.

Table 4-1 lists information necessary for the design and decision making process. As with any checklist, some of the information may not be available initially, but as the project progresses this information should be compiled. This information, which is necessary for the selection and design for a radionuclide system, may also be useful in reviewing current operations and for future planning.

TABLE 4-1

RADIONUCLIDE REMOVAL SYSTEM DESIGN CHECKLIST

---

1. Determine Treatment System Capacity

Daily (24-hour) Product Water Requirements, (gallons)
Initial _____ After 1 year _____ After 3 years _____

Peak (24-hour) Product Water Requirements (gallons)
Initial _____ After 1 year _____ After 3 years _____

Do water requirements include:
Fire protection? yes _____ no _____
Daily maintenance shutdowns? yes _____ no _____
Storage requirements (24 hours)? yes _____ no _____
If yes, gallons __________

2. Determine Raw Water Quality
Total Hardness (as $CaCO_3$) mg/l __________

Radionuclides
Radium 226 and Radium 228 (pCi/l) __________
Uranium (pCi/l) __________
Total Suspended Solids (mg/l)

Total Dissolved Solids (mg/l)
Metals
    Iron (Fe) (mg/l) ________
    Manganese (Mn) (mg/l) ________

pH
Temperature (°F) min _____ mean _____ max _____
Turbidity (NTU) ________
Silt Density Index ________
Hydrogen Sulfide (mg/l) ________
Carbon Dioxide (mg/l) ________

Taste and Odor ________
Color ________

3. Available Space
    Is indoor space available? yes _____ no _____
    If yes, dimensions. (ft)
        length _____ height _____ width _____
    If no, land availability. length _____ width _____
    Access? ____

4. Disposal of Treatment Residues

    a. Availability of Disposal Options

    Discharge to:
        Sanitary Sewer ________
        Receiving Water ________
        Sanitary Landfill ________

    Storage:
        Lagooning ________
        Sanitary Landfill ________
        Strip Mines and Quarries ________
        Land Spreading ________

    Disposal
        In Deep Aquifers ________
        In Oil Well Fields ________
        As a Low Level Nuclear Waste ________

    b. State Local Regulatory Restrictions Applicable to Available Disposal Options (Contact Appropriate State Agency)

5. Desired Finished Water Parameters

    Radium 226 and Radium 228 (pCi/l) ________
    Uranium (pCi/l) ________
    Hardness ($CaCO_3$) (mg/l) ________
    Color ________
    Turbidity (NTU) ________

Odor __________
Pressure (psig) required for distribution __________
Iron and Manganese (mg/l) __________
Chlorine Residual (mg/l) __________

6. Availability of Utilities

Electricity:
Voltage _____ Phase _____ Cycles _____
Cost $__________/kwh

Steam
Pressure _____ (psig)
Standard Cubic Feet/Minute (SCFM) __________
Cost $__________/lb

Air
Plant _____ (psig). _____ (SCFM)
Instrument _____ (psig). _____ (SCFM)
Cost $__________/SCFM

7. Labor

Category	Cost $/hr
Foreman	__________
Class A Operator	__________
Class B Operator	__________
Class C Operator	__________

8. Available Funding

Sources	Interest Rate %	Term (years)
Private ________	_____	____________
Bond ________	_____	____________
Local Government ________	_____	____________

When using this checklist, if the reader is unfamiliar with terminology or with the calcuation or identification of information, it is suggested he consult a suitable reference text such as: a state published operator training guide, the Ten States Standard for Potable Water Quality, or The American Water Works Association publications such as "Water Treatment Plant Design" (1969).

As the investigation, design, and selection of a radionuclide removal system is continued and vendors are contacted, additional information helpful to the design, selection, or implementation process may be obtained. It is suggested that this information also be recorded on the design checklist.

SELECTION OF A RADIONUCLIDE TREATMENT SYSTEM

Once characteristics of the water and any existing treatment system have been compiled, several preliminary decisions regarding the selection of the radionuclide removal system can be made. There are five general criteria for selection of a treatment system, namely:

- o Technical feasibility.
- o Cost,
- o Site limitations,
- o Compatibility with existing treatment, and
- o Preference

The performance and operation of the three treatment processes were discussed in Section III. Potential use and limitations of each technology were discussed, but will be readdressed in this section to direct the designer to the treatment process which may be technically feasible and to eliminate any process which may not be suited to a particular water or site.

Technical Feasibility

Limitations of Lime-Soda Softening for Radionuclide Removal

Lime softening is generally not the treatment of choice for waters with total hardness above 400 mg/l if it is the sole treatment process. There are two reasons for this: (1) the total dissolved solid (TDS) in the water would most likely be above 750 mg/l and, therefore, even after treatment the TDS would remain above the 500 mg/l required by the secondary drinking water regulations, and (2) the cost of chemicals and handling requirements would make the process impractical, especially for the small user.

To use this process for radium removal effectively, the radium concentration should be less than 25 pCi/l, then an 80 percent removal would be sufficient to meet the 5 pCi/l MCL. As discussed in Section III, this is an appropriate upper limit of technology. Because of the limited data on uranium removal by lime-soda softening and the high pH (above 10.6) observed to be necessary in bench studies, lime-soda softening may not be applicable to waters contaminated wth uranium.

Another limitation of the technology is the volume of water to be treated. Systems where less than about 75,000 gallons per day are treated may find difficulty obtaining appropriate equipment. The required labor for maintenance and operation of a lime-soda softening system may also be beyond the available labor support.

Limitations of Ion Exchange for Radionuclide Removal

With proper identification and implementation of pretreatment processes, ion exchange is capable of removing radium or uranium from most water supplies. However, waters with total dissolved solids (TDS) much above 500 mg/l are not amenable to treatment by ion-exchange systems using salt as a regenerant because of the resulting increase in TDS. As discussed in Section III, calcium ions will be exchanged by sodium ions, thus the discharge from the ion-exchange column will be increased in sodium concentration. If the water prior to possible treatment by ion exchange contains an appreciable concentration of sodium, the use of ion exchange should be carefully considered to ensure the drinking water limitations for sodium are not exceeded.

The disposal of regenerant brine and backwash water may restrict the use of the ion-exchange technology. If brine disposal is not permitted due to local regulations or to lack of a suitable nearby disposal site, then ion exchange may not be a feasible alternative or may be too costly.

Because of the limited, although favorable, data on uranium removal using an anionic ion-exchange resin, the use of this technology on waters containing uranium should be carefully considered and performance verified by experimental study before the preparation of a system design.

Limitations of Reverse Osmosis for Radionuclide Removal

Reverse osmosis (RO) has been used to effectively remove the naturally occurring radionuclides, radium and uranium as well as man-made radionuclides. Reverse osmosis can be applied to most contaminated sources effectively if a sufficient number of RO modules are used, membranes are properly selected, and required pretreatment is applied. Reverse osmosis treatment of water can be limited by the presence of several constituents of the untreated water, but is generally applied to systems where high purity water is required and is normally applied after one or more pretreatment steps. Waters which contain high concentrations of calcium carbonate or calcium fluoride, and the sulfate salts of calcium, strontium, or barium may require pretreatment by adjustment of the pH or by the addition of an inhibitor. If these salts are present in high concentrations and pretreatment is not practiced, they may precipitate on the membrane, thereby restricting the passage of water. Likewise, oxides of iron and manganese will also foul the membrane. Pretreatment can be used to remove or "tie up" these compounds and allow treatment by RO.

Suspended solids and particle size must be controlled to ensure successful RO treatment. Suspended solids entering the RO membrane must be kept low to permit operation of the system. Particle size of solids entering the RO membrane are generally kept below a 10 micron particle size by means of an in-line cartridge filter.

The use of RO is also limited by the presence of colloidal materials. Colloids are finely dispersed particles that are difficult to remove by conventional filtration techniques. The RO membrane will not permit the passage of these materials and with time they will plug the membrane and prevent passage of water. An index used to measure potential colloidal interference is the Silt Density Index (SDI), which is discussed in detail in Section III. Most waters have an SDI of less than 3. RO is generally not applicable to waters with SDI's of above 6.

Temperature is also a limitation in the design of an RO system. Most RO membranes are made to operate at temperatures below 95°F. However, even at lower temperatures, RO membrane performance is temperature dependent. The higher the temperature, the faster the membrane loses its capacity to reject dissolved materials. In addition, the long-term performance of the membrane is less at higher temperatures than at lower temperatures.

Cost

In selection of any treatment process, the initial and operating costs are important considerations. Initial costs generally increase as the volume of water treated increases, while unit operating costs generally decrease. Of the three processes considered, lime-soda softening is the most labor and chemical intensive. Reverse osmosis, because of the high pressure pumps required for operaton, has the highest energy cost. Methods to determine initial and operating costs for the three technologies are presented in Section VI. It is suggested that several manufacturers be contacted to obtain costs more specific to the individual site.

When considering costs, a system with higher initial costs should not be immediately ruled out until after operating costs and other factors discussed in this manual have been considered. For example, an ion-exchange system may be far less expensive to purchase than a similar capacity reverse osmosis system, but convenient disposal of the brine regenerant may not be possible, or may be so expensive as to overcome the advantage of the lower capital cost.

Site Limitations

Site-specific limitations will impact the choice of the equipment as heavily as does the raw water quality. Table 4-2 lists several site restrictions to be considered. The space available for locating the system should be measured and assessed for suitability for erecting a system. Plans should be modified, if necessary, to obtain public acceptance of the treatment system and location. In communities where the public participates in decision making, such as in condominiums, public participation in the selection of the plant site and treatment system may not only be convenient, but necessary. Local zoning, construction, and permit requirements should be investigated and addressed.

Although the systems can be automated, maintenance by an operator is required on a routine basis. If a system smaller than required is installed, it may be operated more frequently or at greater rates requiring more frequent and extensive maintenance. This will not only increase treatment costs, but the need for skilled operators, as well.

Provisions for removal of treatment sludges and disposal of regenerants or rejected portions (reverse osmosis) should be investigated from regulatory and handling viewpoints.

The choice of construction materials is also dependent on the individual site chosen. If the facility is to serve the community for a number of years rather than on a temporary basis, then more costly corrosion-resistant materials should be chosen, although

TABLE 4-2

SITE LIMITATIONS AFFECTING TREATMENT SELECTION

Site Limitations
Disposal of Rejected Portion and Treatment Sludges
Space
Available Finished Water Storage
Maintenance
Regulatory Requirements
Expansion (Demand)
Availability of Trained Personnel
Chemical Storage Availability
Frequency of Operation
Maximum Anticipated Idle Period

Source: ESE, 1981.

similar, less-expensive equipment may be available. This less-expensive equipment, however, may be subject to greater corrosion.

Compatibility with Existing Treatment Equipment

For water supplies where some form of treatment is already being applied, the incorporation of as much of the existing equipment as possible may be advantageous from a cost, as well as a technical, perspective. Filtration and disinfection by chlorination are the predominant forms of treatment for the small utility. If the raw water is currently being filtered, filtration would most likely continue to be required prior to the ion-exchange or reverse osmosis system. The ion-exchange contactors or reverse osmosis modules may be added on, perhaps, directly after the filters. Chlorination of the effluent from either process is still required.

Lime-softening, however, may be more difficult to add on since filters are required after the lime-softening process. Use of lime-softening would require more piping changes and perhaps replacement of existing pumps.

Preference

The final selection of a process may not be clearly indicated by performance limitations, costs, or site-specific limitations. The choice of the system may be more of preference. The local developer or residents may not wish an unsightly storage or process tank needed for lime-soda softening, but rather may prefer a housed system. Ion-exchange columns and reverse osmosis systems are generally placed inside a building.

Other preferences may be based on the availability of operating and maintenance personnel or on the adaptability of the system to expansion. The lime-soda softening process requires greater and more frequent attention than do the other processes. It is also easier to add on reverse osmosis modules or ion-exchange columns (assuming pretreatment is adequate) than to expand a lime-softening system.

PILOT STUDIES FOR EVALUATING RADIONUCLIDE REMOVAL PROCESSES

The technologies which effectively remove radionuclides from water; lime-soda softening, ion exchange, and reverse osmosis; have been extensively studied for hardness or dissolved solids removal. The effectiveness of these technologies to remove hardness and other dissolved materials from water, including radium, is well documented. Their use, however, for removal of uranium has not been investigated in detail. The effects of raw water characteristics on the performance of each of these technologies for hardness or TDS removal is understood and can be predicted. From the raw water characteristics, most design criteria for radium removal for each of the systems can be developed either through water chemistry, established design correlations, or manufacturer experience. Pilot studies are, therefore, not generally necessary to confirm removal of radium or to establish design criteria for these processes. Batch tests called isotherms, which consist of shaking a resin with the water to determine the capacity of a resin, however, may be conducted by a manufacturer to determine the best resin for the ion-exchange process. The cost of conducting a pilot study, especially if radionuclides are to be monitored, can be a major portion of the total engineering and construction costs for the project.

Because of the limited data on the removal of uranium, laboratory or bench studies should be considered. Since only ion-exchange and reverse osmosis are considered technically feasible for removal of uranium, studies first using an anionic exchange resin and then using reverse osmosis should be conducted. This order is suggested because if ion exchange is not satisfactory, the choice becomes one of selecting the most appropriate reverse osmosis membrane and system.

DESIGN OF A LIME-SODA SOFTENING SYSTEM FOR RADIUM REMOVAL

As discussed in Section III, the lime-soda process is used to remove calcium and magnesium ions from water in a softening plant. It also removes radium along with the other metals because radium is chemically similar to calcium and magnesium. If the plant is to be designed or operated for radium removal rather than softening, the operating conditions might be quite different. For example, Figure 3-5 showed that increasing the pH from 8.0 to 9.5 has little effect on radium removal but that change could have a noticeable effect on softening.

Analysis Required for Designing A Lime-Soda Softening System for Radium Removal

To estimate the amounts and kind of chemicals to be used and to size the plant, the following parameters should be determined:

A. Chemical
  1. pH;
  2. TDS, mg/l;
  3. Total Alkalinity, mg/l as $CaCO_3$;
  4. Calcium, mg/l as $CaCO_3$;
  5. Magnesium, mg/l as $CaCO_3$;
  6. H_2S, mg/l; and
  7. Radium, pCi/l.

B. Physical
  1. Temperature, °C or °F;
  2. Peak demand, gpd; and
  3. Average demand, gpd.

Pretreatment Prior to the Lime-Soda Softening Process

Because of the high pH of softening and the long reaction times in the treatment plant, the usual contaminants that require pretreatment are removed in the softening step. The exceptions may be carbon dioxide and hydrogen sulfide.

Since CO_2 reacts with lime and H_2S has a bad odor, some plants aerate the raw water for the removal of either or both of these before softening. Unless the amounts are relatively high, it is usually better to avoid aeration. Aeration saturates the water with dissolved oxygen (DO) which makes it much more corrosive, leading to or aggravating red water problems and water main deterioration if iron pipe is in use.

Design Criteria for the Lime-Soda Softening Radium Removal Process

To design a lime-soda softening plant for radium removal, it is necessary to decide what type of plant to consider. The two general types are the horizontal flow plant with separate mixing, flocculation, and sedimentation basins, and the up-flow unit in which all the mixing and settling take place in the same basin. Most small plants and many large softening plants use the latter type because it requires less space and energy. Up-flow units use less space because they are designed to mix recycled sludge with the water being treated. This improves the rate at which the precipitates are formed and makes the particles much larger. Therefore, they settle much faster allowing the use of a smaller volume for sedimentation. The information needed to design the up-flow type unit more commonly used for small water systems are:

1. Settling velocity of solids formed. This is used to determine the surface loading rate of the sedimentation section of the unit (4 cm/min settling velocity equals 1 gal/min-ft^2).

2. Hardness removal (and, therefore, radium removal), which is necessary in order to determine the amount of sludge that will be generated and which then must be disposed of.

3. Settled water turbidity in order to estimate the type of filter design and filter backwash required.

4. Maximum daily demand to be used for sizing the units.

5. Dosages of chemicals for sizing feeders or solution tanks.

Factors Which Influence Chemical Dosage in the Lime-Soda Softening Process

Of the factors that must be considered in designing the treatment system, several affect the type and amount of chemicals to be fed into the untreated water. Lime (CaO) and soda ash (Na_2CO_3) are the two chemicals used in this process. Terms necessary to the discussion of the softening process include:

1. Total hardness--the total of the calcium plus magnesium hardness.

2. Carbonate hardness--that part of the total hardness which is equivalent to the total alkalinity; all forms of hardness and alkalinity are expressed as mg/l of calcium carbonate ($CaCO_3$).

3. Noncarbonate hardness--all of the total hardness that is not carbonate hardness. That is, the total hardness minus the carbonate hardness or alkalinity equals the noncarbonate hardness expressed as mg/l $CaCO_3$.

4. Excess alkalinity (XS) of 35 mg/l as $CaCO_3$--this is an average value to raise the pH to the point where magnesium will precipitate as $Mg(OH)_2$. Although the exact value is hard to calculate, it can be measured through laboratory analysis.

In most cases where the process is being designed for radium removal rather than for softening, it is possible to ignore magnesium removal. Then, the only consideration is calcium removal, which uses less lime and soda ash.

As discussed in Section III, radium is removed in the softening process along with the hardness-causing ions of calcium and magnesium. Therefore, in designing the softening process or in estimating chemical dosages, only the requirements to obtain softening and the relationship between radium removal and hardness removal need to be considered.

The amount of hardness removal necessary to remove a certain amount of radium, for example, can be estimated with the aid of Figure 3-4 (fraction of total hardness removed versus fraction of radium removed). The amounts of lime and soda ash to be used can be estimated from the equations presented in the following discussion, but should be tested first in laboratory analysis. Adjustments can then be made in dosages to attain the radium and hardness removals necessary.

Sample Design of a Lime-Soda Softening Process for Radium Removal

Background

A small utility supplies an average of 300,000 gallons of water per day. Its well supply was analyzed and found to contain 25 pCi/l of radium. The total hardness of the water was 240 mg/l as $CaCO_3$ with 10 mg/l present as magnesium hardness. The alkalinity was 220 mg/l, while the free carbon dioxide content was 40 mg/l. Currently, the utility only chlorinates the water. Lime-soda softening is being considered for radium removal if that would solve the problem.

Step 1 - Calculate Required Hardness Removal

The first step would be to calculate the amount of hardness to be removed along with the radium so that the radium level would be less than 5 pCi/l.

The fraction of radium to be removed would, therefore, be:

$$\frac{25\ \text{pCi/l} - 5\ \text{pCi/l}}{25\ \text{pCi/l}} = 0.80 \text{ or } 80 \text{ percent}$$

From Figure 3-4, it can be *estimated* that this fraction of radium removal would require about 50 percent (0.50) hardness removal. This means that 50 percent of the original total hardness of 240 mg/l, or 120 mg/l would have to be removed. Since the carbonate hardness was 220 mg/l (equal to the alkalinity), 120 mg/l of calcium carbonate hardness would have to be removed by reacting with lime added for the treatment process. Since the water contained 40 mg/l of CO_2 (as $CaCO_3$) this, too, would react with lime.

If all of the carbonate hardness were to be removed, the final hardness would be about 65 mg/l (35 mg/l as calcium because of its solubility, 20 mg/l of noncarbonate hardness and 10 mg/l as magnesium, since none need be removed. The hardness removed is therefore:

$$\frac{240\ \text{mg/l} - 65\ \text{mg/l}}{240\ \text{mg/l}} = 73 \text{ percent}$$

which is above the 50 percent hardness removal necessary to reduce the radium concentration to 5 pCi/l. Therefore, only the 120 mg/l needs to be reacted with lime plus about 35 mg/l as $CaCO_3$ for the solubility.

Step 2 - Determine Lime Requirements

The amount of lime needed is determined by using the following set of simple equations for estimating the chemical dosages:

1. Removal of carbonate hardness and magnesium: pounds/million gallons (lb/MG) of 100 percent quicklime (CaO) = (56/44 x 8.34) (CO_2 in mg/l) + (56/100 x 8.34) (alkalinity in mg/l as $CaCO_3$ + magnesium hardness in mg/l as $CaCO_3$ + excess of about 35 mg/l as $CaCO_3$).
2. Removal of noncarbonate hardness: lb/MG of 100 percent soda ash (Na_2CO_3) = 106/100 x 8.34 = 8.8 (noncarbonate hardness in mg/l as $CaCO_3$ - noncarbonate hardness remaining in the softened water).

Step 3 - Correction for Lime Purity

It is assumed that the small water system would purchase lime already in the slaked form and not of 100 percent purity, hence, the dosage must be corrected for purity.

The correction for the percent purity is made by dividing the calculated dosage by the purity, that is, the percent purity divided by 100. Example: a dosage of 150 lb/MG of 100 percent CaO would be 161.3 lb/MG of 93 percent pure commercial quicklime (CaO). Calculated as: 150 lb/MG ÷ 0.93 purity = 161.3 lb/MG.

The correction procedure for hydrated lime instead of CaO is to multiply the CaO dosage by 74/56 = 1.32 [the ratio of the respective molecular weights, i.e., hydrated lime (74) to that of calcium oxide (56)]. Soda ash dosages do not need to be corrected since commercial grade is almost 100 percent pure.

Step 4 - Summary of Chemical Requirements

For this example, then, the chemical requirements are:

lb/MG of 100 percent pure CaO = 10.6 (CO_2, mg/l)

+ 4.7 (alkalinity, mg/l as $CaCO_3$ + 35 mg/l XS)

= 10.6 (40) + 4.7 (155) = 1,152.

This is 1,152 x 74/56 = 1,522 lb/MG 100 percent $Ca(OH)_2$ or 1,637 lb/MG of 93 percent $Ca(OH)_2$.

Step 5 - Daily Chemical Usage

For a plant flow of 300,000 gpd, then, the actual daily chemical usage would be:

$$\frac{0.3\ \text{MG/day}}{1.0\ \text{MG/day}} \times 1{,}637\ \text{lb/MG} =$$

491 lb/day of 93% $Ca(OH)_2$

This could be used as a starting point in a laboratory study to check its accuracy. [For laboratory studies this would be equivalent to 182.5 mg/l of laboratory grade, 100% $Ca(OH)_2$.]

The plant should be designed, however, to treat at least twice the average flow to meet peak demands. Therefore, the chemical storage facility should be sized to feed chemicals to a 600,000 gpd plant, or about 1,000 lb/day of lime.

Step 6 - Sizing of Treatment Unit

Results from laboratory studies recommended for evaluating the lime-softening process showed a settled water turbidity of less than 5 NTU could be obtained at a settling velocity of 10 cm/min (or 2.5 gpm/ft^2 surface loading rate). Five (5) NTU is the amount of turbidity considered to be suitable as influent to polishing filters without causing operational problems. This settling velocity or surface loading rate allows the calculation of the minimum size of the treatment unit. For 600,000 gpd, this is a surface area calculated as:

$$\frac{600{,}000\ \text{gpd}}{1{,}440\ \text{mpd}} \times \frac{1\ \text{ft}^2}{2.5\ \text{gpm}} = 167\ \text{ft}^2$$

or a circular unit with about a 15-foot diameter. This must be increased to account for the area to be occupied by the central mixing zone.

Filters must be included to polish the water (remove any unsettled particles) before distribution in order to meet the 1 NTU turbidity standard.

Laboratory Studies

Although chemical dosage can be estimated from the equations presented, small scale studies in the laboratory, called "jar tests," can determine the amounts of chemicals required to obtain the radium removal necessary. These studies can also test different substances that increase the settling rate of the precipitates, so-called coagulant aids. The results of the jar test can then be used to specify the type of chemical coagulant and the required dosage.

DESIGN OF AN ION-EXCHANGE TREATMENT SYSTEM FOR RADIUM REMOVAL

Ion-exchange treatment for the removal of radionuclides was discussed in Section III. Cation exchangers can remove more than 95 percent of radium applied to the resin column and can be regenerated, following exhaustion, using a concentrated salt solution. Uranium removals of 99 percent through an anion exchange resin such as Dowex 1-X2, have been shown to be possible in laboratory studies when followed by regeneration with mixed sodium chloride and sodium bicarbonate solution. Only radium removal, however, is considered in this section since its removal by resins has been more thoroughly studied. The operational cycle of the ion-exchange column was discussed in Section III. Also presented were several design and operational concerns. The performance and operational requirements of each of the sequences in the cycle, radionuclide removal - exhaustion-regeneration-backwash, dictate the design of the column, regenerant storage, and waste stream disposal. The raw water analysis will reveal pretreatment requirements which can be further determined through bench or pilot testing.

Pretreatment Prior to an Ion-Exchange System

The ion-exchange resin is a spherical, synthetic bead of uniform shape and particle size. When placed into a column, the beads provide filtration of suspended matter and act as potential sites for promoting biological growths. Filtered suspended matter and biological slime growths will reduce the hydraulic capacity of the resin or perhaps cause the feed water to channel around the resin. If this occurs, the water to be treated will not make proper contact with the resin, which results in decreased performance. Generally, waters with turbidity above 2 NTU's are pretreated by sand filtration before ion exchange.

If bacteria are present in the water supply, prechlorination can provide sufficient control to prevent biological growths within the resin column.

The cation exchanger will remove calcium and magnesium ions as well as those of the radium. High hardness will exhaust the capacity of the bed more rapidly. Thus, the column size must be increased or the frequency of regeneration will have to be increased substantially increasing the operational costs. For these cases, a cost comparison should be made between lime-soda softening and ion-exchange softening.

For most waters, especially for the removal of uranium by an anion exchange resin, pH adjustment will be necessary, either to obtain desired removals or to optimize the performance of a specific resin on a particular water supply.

Analysis Required for the Design of an Ion-Exchange System for Radium Removal

Table 4-3 lists information that is necessary for the design of a radium removal system, including ion-exchange treatment. It also aids in developing a complete understanding of the present treatment system, or in the determination of future needs.

The use of these parameters has been discussed in the section regarding consideration of pretreatment processes. With the exceptions of the radium concentration, these analyses may already be performed routinely. Certified laboratories should be contacted for any analyses not done at the plant.

Pilot Testing of Ion-Exchange Systems for Radium Removal

Following the characterization of the raw water, including the parameters listed in Table 4-2, a resin manufacturer, or an equipment supplier (Table 3-3) should be contacted. The vendor, after reviewing the analysis and the utility's needs, may suggest bench isotherm tests before recommending a resin or a system. The vendor, in most cases, can perform these tests on a sample of the water. The isotherm, which determines capacity of a resin for removing an ion, is useful in determining whether the desired removal can be obtained for a particular water. In addition, isotherms are useful in determining relative performance of the resins tested, the optimum

TABLE 4-3

ANALYSIS REQUIRED FOR DESIGNING AN ION-EXCHANGE SYSTEM FOR RADIUM REMOVAL

- Peak water demand, gpd __________
- Average water demand, gpd __________
- Radium concentration, pCi/l __________
- Total hardness, mg/l __________
- pH __________
- Total dissolved solids, mg/l __________
- Turbidity, NTU __________
- Temperature, minimum °F __________

pH range, approximate regenerant requirements, and pretreatment requirements. Since hardness removal is an indicator of the capacity of a resin to remove radium, the manufacturer may choose to base performance on using the inexpensive analysis of hardness rather than the more costly radium analysis.

Design Criteria for an Ion-Exchange System for Radium Removal

As previously discussed, there are four cycles comprising the operation of an ion-exchange system; removal-exhaustion-regeneration-backwash. Each is dependent upon a characteristic of the water, and impact on the design criteria. The removal cycle is dependent on the radium concentration and the volume of water to be treated. This determines the type of resin and, combined with the capacity of the resin for hardness removal, determines the volume of resin material required to treat the water between regenerations. This also determines the run time (or volume of water that can be treated) prior to exhauston. The volume of regenerant required after each removal cycle depends on the volume and type of resin. The size of the regenerant tank and disposal system is then determined from the regenerant requirements.

The backwash rate is determined by the type of resin and the temperature of the water. Once the backwash rate is established the overall height of the column can be calculated.

The basic parameters that must be established to specify a radium removal system are listed in Table 4-4.

Sample Design of an Ion-Exchange System for Radium Removal

Step 1 - Select Resin and Determine Capacity for Radium Removal

Resin selection is dependent on the water analysis, results from pilot testing, if conducted, and manufacturers' recommendations. Table 3-3 lists suppliers of ion-exchange resins and system vendors. The manufacturers will provide detailed application guides and pretreatment requirements for their resins or equipment. The manufacturers should provide information in terms of resin capacity or run length. Resin capacity can be measured as the gallons of water which can be treated per cubic foot of resin to the point of exchange exhaustion. Exhaustion occurs when the exchanger fails to provide the degree of contaminant removal necessary to maintain acceptable water quality. At exhaustion the exchanger is removed from service and regenerated.

If a manufacturer supplies a modular system with a fixed volume of resin, then based on past experience or pilot or bench studies, a run length in terms of service hours for production of acceptable water will be provided.

Step 2 - Blending

Since ion exchange can remove up to 95 percent of the radium present, not all the flow may need to be treated. As discussed in Section III, a portion of the water can be blended with the untreated water to provide a treated water meeting the MCL.

TABLE 4-4

BASIC DESIGN INFORMATION FOR ION-EXCHANGE SYSTEM

Flow, gpd

Resin type

Resin volume, ft^3

Column diameter, ft

Column height, ft

Surface loading rate, gpm/ft^2

Backwash flow rate, gpm/ft^2

Bed expansion at backwash flow rate, percentage (%)

Service cycle time, hrs

Regenerant dosage, lbs regenerant/ft^3 resin

Volume of regenerant, gal/cycle

Regenerant flow rate, gpm/ft^2

Regenerant contact time, min

Regenerant storage volume, gal

As an example, assume a utility supplies water to a small community. The ground-water source has been found to have 10 pCi/l of radium present. Purchased water from a nearby municipality has been investigated, but is considered too costly. Water demands are projected to be at most 250,000 gallons per day for the next 3 years. Ion exchange is being considered as a preferred treatment alternative. Since the system will remove up to 95 percent of influent radium concentration, blending with untreated water should be considered to minimize the size of the system. Figure 4-1 relates the fraction of water that needs to be treated for various raw water influent radium concentrations. This figure is based on a performance efficiency of 95 percent radium removal and assumes that the ion-exchange resin will be exhausted when removal drops below 95 percent. Before using this figure, testing should be performed with one or more resins to confirm that such removals are possible with the water to be

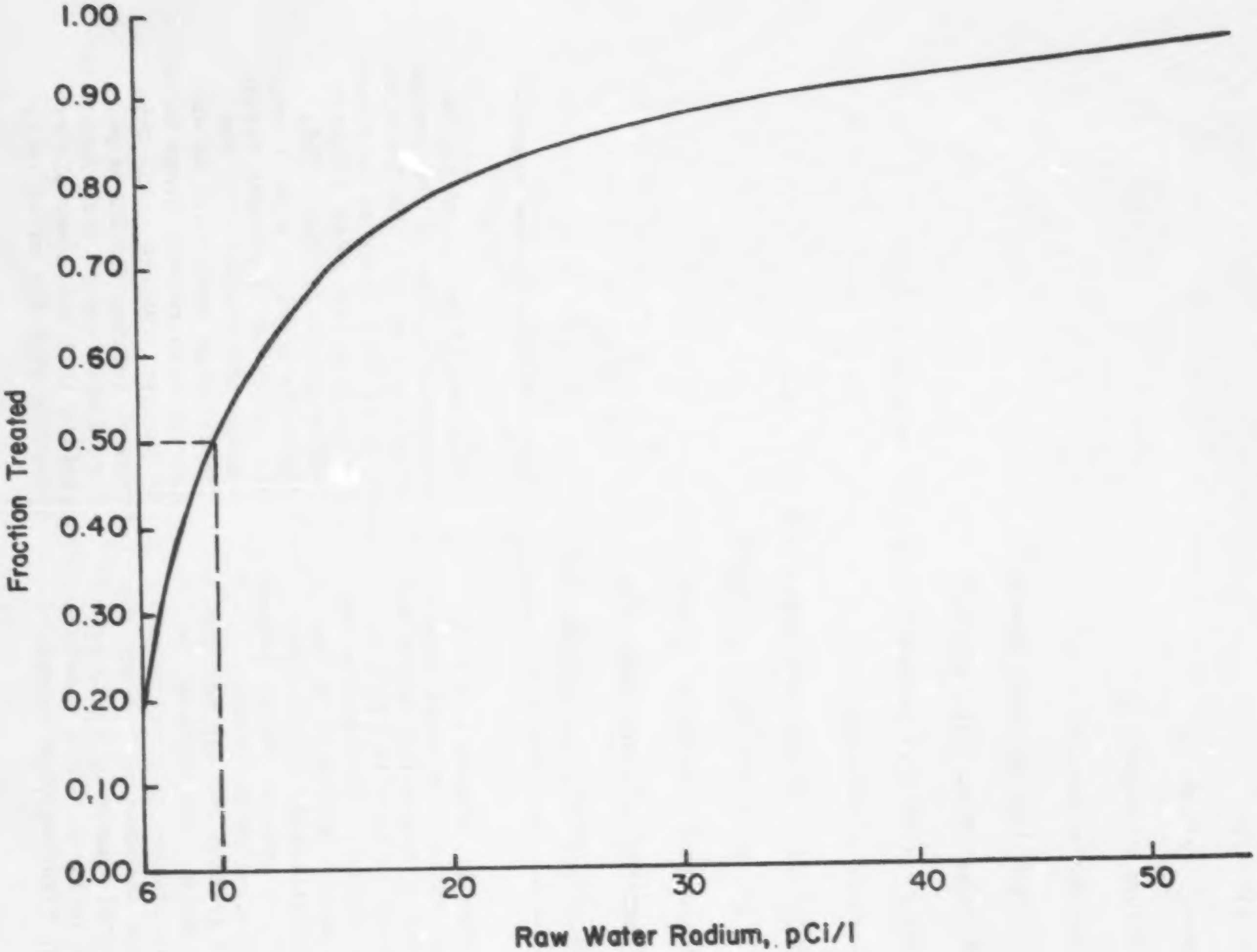


Figure 4-1. Fraction of Water Needed to be Treated Versus Raw Water Radium Concentration to Obtain Final Concentration of 5 Pic/1 - Ion Exchange (95% removal efficiency)

treated. For this example, if 95 percent radium removal were confirmed, then from Figure 4-1 for a raw water concentration of 10 pCi/1, 50 percent of the flow (or 125,000 gpd) requires treatment.

If, however, only 90 percent removal and not 95 percent removal were possible, the fraction treated would be calculated by using the following equation:

$$f = \frac{C_i - C_o}{C_i e}$$

where:

f = fraction treated

C_o = desired concentration of radium after treatment (5 pCi/1 for this example)

C_i = untreated water radium concentration (10 pCi/1 for this example)

e = efficiency of treatment system (90% or 0.9 for this example)

therefore:

$$f = \frac{10-5}{(10)(0.9)} = \frac{5}{9} = 0.56$$

Thus, the treated flow would be 0.56 (250,000 gpd), or 140,000 gpd.

Step 3 - Calculate Required Ion-Exchange Bed Volume

The amount of resin required in the ion-exchange system, known as the bed volume (BV), is determined from three factors:

- Specific capacity of the resin
- Desired (assumed) lifetime between regenerations
- Manufacturer's recommended resin bed depth (ft) and surface loading rate (gpm/ft^2)

Assume for this example that the resin can treat 10,000 gallons of water per cubic foot of resin before the resin can no longer remove 90 percent of radium at an influent concentration of 10 pCi/1. This information can be obtained from bench or pilot scale testing. Based on the blending calculation, 140,000 gallons/day requires treatment. If it is decided to regenerate the resin only once per week, the required resin volume is calculated by:

Cubic feet of resin =

$$\frac{\text{Volume of water treated/day x days between regeneration}}{\text{Resin Capacity (gallons/cubic foot)}}$$

$$= \frac{140{,}000 \text{ gpd x 7 days}}{10{,}000 \text{ gal/ft}^3}$$

$$= 98 \text{ ft}^3$$

The manufacturer will specify surface loading rates and minimum acceptable bed depths for the resin bed as well as backwash flow rates. A minimum bed depth is required to provide sufficient contact of the water with the resin to assure that the required levels of contaminant removal are met.

For this example, assume that the manufacturer recommends a surface loading rate of 4 gpm/ft^2, a minimum resin depth of 30 inches, and a backwash rate of 8 gpm/ft^2.

The column diameter for a single column would be calculated as:

Total flow (gallons/minute, gpm) = surface area (ft^2) x surface loading rate (gpm/ft^2)

$$\text{Flow} = \frac{140{,}000 \text{ g/day}}{1{,}440 \text{ min/day}} = 97.22 \text{ gpm}$$

Area (ft^2) =

$$\frac{\text{flow}}{\text{surface loading rate}} = \frac{97.22 \text{ gpm}}{4 \text{ gpm/ft}^2}$$

$$= 24.3 \text{ ft}^2$$

Also area = $\pi r^2 = \pi \frac{D^2}{4}$

Then diameter of column = D =

$$\sqrt{\frac{4 \text{ Area}}{\pi}} = \sqrt{\frac{(4)(24.3)}{\pi}}$$

$$= 5.56 \text{ ft}$$

This should be rounded to the next higher whole number, i.e., 6 ft, as a standard size.

The bed depth would be based on:

Volume (ft^3) = $\pi r^2 h$

$$\text{or } h = \frac{V}{\pi r^2} = \frac{98 \text{ ft}^3}{\pi (3 \text{ ft})^2} = \begin{matrix} 3.47 \text{ ft} \\ \text{or} \\ 42 \text{ in} \end{matrix}$$

This is greater than the minimum required depth of 30 inches.

Step 4 - Calculation of Column Dimensions

The diameter of the column would be 6 feet as calculated. The column sidewall height will be determined from the calculated resin depth and a freeboard allowance for backwashing. Backwashing is required following regeneration to remove residual regenerant and to wash out any suspended solids that have been removed through filtration.

Backwash allowance is dependent upon the size and density of the resin with expansion of the resin a function of backwash flow rate. Curves are provided by the manufacturers which relate expansion to backwash flow rate (gpm/ft^2). Backwash expansion is temperature dependent with greater expansion at lower temperature. This dependency is related to the viscosity of water which is temperature dependent. Manufacturers provide expansion curves for several temperatures. If a curve is not provided for a temperature near the minimum operating temperature, then the expansion can be calculated by knowing that the percent expansion is directly related to the viscosity, or

$$\frac{E_1}{E_2} = \frac{V_1}{V_2}$$

For example, at a backwash flow of 8 gpm/ft^2 and a temperature of 70°F, the expansion determined from the curve is 25 percent (E_1). The expansion at 50°F (E_2) would be calculated from the relationship

$$\frac{E_1}{E_2} = \frac{V_1}{V_2} \quad \text{or}$$

$$E_2 = \frac{E_1 V_2}{V_1}$$

$$E_2 = \underline{\%\text{ expansion at } 50°\text{F}} = \frac{(\text{viscosity at } 50°\text{F})(E_1)}{(\text{viscosity at } 70°\text{F})}$$

from a handbook such as the Handbook of Chemistry and Physics (CRC Publishing Company), the viscosities are 0.9810 centipoises at 70°F and 1.3077 centipoises at 50°F.

The % expansion is then =

$$25\ \frac{(1.3077)}{(0.9810)}$$

or = 33%

Thus, at this temperature and for backwash flow rate of 8 gpm/ft^2 and a resin depth of 42 inches, the required column residual height is 42 x 1.33 = 56 inches. Therefore, the column would be 6 feet in diameter and at least 56 inches in height.

Step 5 - Calculation of Regenerant Requirements and Sizing of Regenerant Storage Volume

The regenerant volume and concentration are dependent on the specific resin. This information is provided by the resin manufacturer based on similar applications. The regenerant volume used per cycle may vary from site to site and sufficient extra capacity should be provided in the regenerant storage tank to allow for possible greater regenerant use than initially anticipated.

For this example, assume that 15 pounds of sodium chloride prepared in a 10 percent by weight solution is necessary to regenerate a cubic foot of resin. Therefore, for the 98 cubic feet of resin:

$$98 \text{ ft}^3 \times 15 \text{ lbs/ft}^3 =$$
1,470 lbs of sodium chloride

The volume (gallons) of regenerant for a 10 percent by weight solution would be calculated as follows:

$$\frac{1{,}470 \text{ lbs of salt}}{\frac{1 \text{ lb of salt}}{10 \text{ lbs of water}} \times \frac{8.34 \text{ lbs of water}}{\text{gallon}} \times \begin{array}{c}\text{Specific gravity of a}\\ \text{10\% brine solution}\end{array}}$$

Specific gravity of brine solutions can be obtained from a reference source, such as the Handbook of Chemistry and Physics. The specific gravity of a 10 percent sodium chloride solution is 1.0707.

Therefore:

$$\frac{1{,}470 \text{ lbs}}{\frac{1 \text{ lb}}{10 \text{ lbs}} \times \frac{8.34 \text{ lbs}}{\text{gal}} \times 1.0707} =$$

1,646 gallons of a 10% sodium chloride solution

Enough storage capacity should be provided for 3 or 4 regeneration cycles. The regenerant flow rate for a 6-foot diameter column with loading at 0.5 gpm/ft^2 is determined as:

$$0.5 \text{ gpm/ft}^2\ \frac{\pi (6)^2 \text{ ft}^2}{4} = 14.1 \text{ gpm}$$

Step 7 - Calculation of Regeneration Cycle Time

The regeneration cycle time is the time required to pass all the regenerant through the resin bed at the desired flow rate. To pass 1,646 gallons through the column at 14.1 gpm would take:

$$\frac{1{,}646 \text{ gallons}}{14.1 \text{ gpm}} = \begin{array}{l}\text{117 minutes (or}\\ \text{about 2 hours)}\end{array}$$

During this time, the resin column would not be processing any water and a second column, or water from storage will be necessary to maintain supply to the distribution system.

Step 8 - Calculation of Radium Concentration in Regenerant Brine

From the example, calculations showed that 1,646 gallons of brine regenerant would be required after processing 7 days. The raw water volume processed during these 7 days is:

7 x 140,000 gpd = 980,000 gallons.

During the treatment of the 980,000 gallons of water, radium will be reduced by at least 90 percent and all the radium in the feed water could be removed. The regeneration step will remove the radium on the resin and transfer it to the brine solution. If a worst case is assumed, 100 percent of the radium is removed in the removal as well as the regeneration cycle, then the concentration in the waste regenerant brine would be calculated as:

$$\frac{\text{(gallons feed water treated in removal cycle) x (radium concentration)}}{\text{(gallons of regenerant)}}$$

or

$$\frac{\text{980,000 gallons x 10 pCi/l}}{\text{1,646 gallons}} =$$

$$\text{5,954 pCi/l}$$

Also as a worst case, no change in the salt concentration in the brine is assumed. This information can then be used in considering waste disposal options.

DESIGN OF A REVERSE OSMOSIS TREATMENT SYSTEM FOR RADIONUCLIDES

The theory of reverse osmosis and a description of the types of membranes currently in use were presented in Section III. Radionuclide removals above 95 percent have been reported in waters treated by RO where radionuclides have been monitored. The selection and design of an RO system consists of evaluating the limitations of the technology, including if applicable, determining if the water can be treated by the reverse osmosis process, determining pretreatment requirements, estimating the number of modules required, and determining post treatment needs and methods.

Analytical Requirements and Plant Operating Information Required for Selection of a Reverse Osmosis System

Table 4-5 lists the analytical data and plant operating information necessary to determine if RO is a viable alternative, the pretreatment needs and the RO system design.

Pretreatment Prior to Reverse Osmosis

As discussed earlier in the section on limitations of the RO process, many materials present in water can foul an RO membrane or reduce performance. One or more pretreatment steps may therefore be required before the RO process. The raw water analysis information, listed in Table 4-5, will help to identify most of the pretreatment requirements. Pilot tests conducted by an RO manufacturer may indicate needs for more or less pretreatment. If calcium carbonate, calcium sulfate, barium sulfate, silica or strontium sulfate are present, then pretreatment to reduce the concentration of these salts may

TABLE 4-5

LIST OF INFORMATION REQUIRED FOR SELECTION OF A REVERSE OSMOSIS SYSTEM

Daily water requirements, gpd __________

Peak water requirements, gpd __________

Temperature (maximum), °C __________

Chemical __________

Radionuclide concentration, pCi/l __________

Total hardness, ($CaCO_3$), mg/l __________

Calcium hardness, mg/l __________

Calcium sulfate concentration, mg/l __________

Fluoride concentration, mg/l __________

Barium sulfate concentration, mg/l __________

Strontium sulfate concentration, mg/l __________

Silica, mg/l __________

Iron concentration, mg/l __________

Manganese concentration, mg/l __________

Total dissolved solids, mg/l __________

H_2S concentration, mg/l __________

Turbidity (NTU) __________

Silt density index __________

Chlorine concentration, mg/l __________

Bacteria MPN __________

Dissolved oxygen concentration, mg/l __________

Carbon dioxide concentration, mg/l __________

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be required. Typical methods of pretreatment include softening by an ion-exchange resin to remove the calcium, barium, or strontium cations. Under these conditions, the pretreatment will reduce radium concentrations also--thereby elmininating the need for RO for radium removal only. pH adjustment may be used to reduce precipitation of carbonates on the membrane. Precipitation is more likely to occur at a pH above 8. Inhibitors such as sodium hexametaphosphate can also be used to minimize salt deposition. Silica scaling can also be limited by adjusting the pH of the water to near pH 7 where silica exhibits its best solubility. It is suggested that several RO manufacturers be contacted to determine if the particular water will cause scaling and what pretreatment is recommended by each resin manufacturer.

If iron and manganese are present in the water supply, pretreatment may be necessary to prevent fouling by their insoluble oxides. Iron oxide is most often the major problem. Iron in ground water is generally present as the soluble ferrous form. As the water contacts air, the iron will be oxidized further to the insoluble ferric oxide form. The iron can be completely oxidized by aeration and then removed by filtration.

Certain ion-exchange resins, such as sodium zeolite, also effectively remove iron. Iron concentrations as high as 4 mg/l can be tolerated in the feed to the RO module if oxygen is not present in the water (less than 0.1 mg/l dissolved oxygen). If dissolved oxygen is present above 5 mg/l, then the iron concentration should be kept below 0.05 mg/l in the RO feed.

Most RO membranes are preceeded by a 5 to 10 micron in-line cartridge filter. This filter prevents plugging of the RO membrane caused by entrapment of suspended particles.

Although RO use may be limited to waters with SDI below 6, several pretreatment methods will reduce the colloidal matter in the water and permit treatment. Nonionic or cationic polyelectrolytes can be added to the water to enhance the coagulation of the fine suspended colloidal particles and permit removal by either sand, anthracite, or diatomaceous earth filters. Bench testing may be required to evaluate performance of various polyelectrolytes and to select the dosage of the best polyelectrolyte. The SDI test should be run on a sample of the water treated with polyelectrolyte to assure the water is acceptable for treatment by RO (SDI less than 6).

Bacteria present in the water may affect the RO membrane either by actual destruction of the membrane or by fouling. Disinfectants such as chlorine or ultraviolet light very effectively control bacterial growths. If the water is chlorinated for disinfection, then the water must be dechlorinated before it is applied to the membrane as chlorine also attacks some membrane materials, even though membranes are available that are chlorine-resistant. If dechlorination is required, passage of the chlorinated water through a granular activated carbon column is effective.

Hydrogen sulfide when present in water supplies may be oxidized in the RO process. Elemental sulfur is a product of this oxidation and will deposit on the membrane. Hydrogen sulfide can be removed by aeration, or if the problem is severe, by chlorination, either of which must be followed by filtration. The adjustment of the Ph to values less than 7 to prevent the precipitation of carbonates will serve to keep the hydrogen sulfide in the gaseous state, which will not foul the membranes. Aeration of the product water removes the hydrogen sulfide effectively, along with the carbon dioxide formed from the carbonates present.

Procedure for Selection of Reverse Osmosis System for Radionuclide Removal

There are five major concerns in the design of an RO system for removal of radionuclides:

1. Flow (capacity)
2. Conversion (removal requirements)
3. Concentration of dissolved material in feed water
4. Feed water temperature
5. Feed water pressure

Based on this information and assuming recommended pretreatment is included, the RO manufacturer can recommend an appropriate system to remove the radionuclides to below the MCL.

The treated flow requirements in gallons per day should be determined from projected demands and consideration of blending with other water sources to achieve compliance. A new RO module can only exceed its specified capacity by, at most, 10 percent. The system will not treat flows above initial rated capacity with reliability. Additional RO modules can be added as needed up to the capacity of the pretreatment or posttreatment systems. Therefore, in the design of an RO system, the pretreatment system may be designed for supplying several more RO modules than initially anticipated.

Conversion is a term used to indicate the percentage of water flow that passes through the membrane. Conversion depends on the concentration and type of dissolved materials in the waters, as well as the membrane type and operating pressure. Conversion rates for other dissolved materials such as sodium chloride also should be obtained from manufacturer, since RO will remove these dissolved ions and they will be present in the reject stream (water which does not pass through the membrane). The concentration of dissolved salts in the reject stream may restrict the disposal to a greater extent than the radionuclides present in this stream.

The feed pump pressure to the RO system dictates the performance of the membrane. Small utilities, in most cases, will purchase the pump and RO modules together as a package and not separately. If pumps are not a part of the package the RO manufacturer will specify pump requirements.

As discussed in Section III, the water temperature significantly affects the capacity of the membrane. Initial membrane capacity is less for lower temperatures, but the rate at which capacity is reduced is accelerated at higher temperatures. For example, at 15°C, the initial capacity of a certain membrane is 74 percent of rated capacity at a pressure of 400 psig. After the first year, the capacity drops to 66 percent and after the second year to 64.5 percent. At 25°C, the initial capacity of the same membrane at 400 psig is 100 percent of rated capacity, but after the first year, declines to 83 percent and after the second, to 80 percent.

Specifying Reverse Osmosis Modules

Equipment vendors supply RO systems to treat flows from as small as a single homeowner's system to as large as a municipal plant supplying more than 10 million gallons per day. Manufacturers can supply complete systems, other than perhaps pretreatment units, incorporating the necessary design of the RO module and auxilliary components. The purchaser generally needs only to provide the vendor with information on raw water characteristics, water demands, storage requirements, and space availability. The vendor will supply the utility or its engineer with a system schematic, such as Figure 4-2, and the specifications and operating ranges for all components. The vendor will also provide a cost estimate for his equipment package.

Step 1 - Capacity

The utility needs to estimate the size requirements for the RO system based on demands and on required radionuclide removal. Since RO will remove 95 percent of the radionuclides (both radium and uranium), it is likely that the treated water can be blended with a portion of untreated water. Using Figure 4-3, if a utility had a radium concentration of 30 pCi/l, then 87 percent of the water flow would require treatment. Following treatment it can then be blended with untreated water to make up the total demand. It should be remembered that the volume of water applied to an RO system is not the output of permeate passing through the membrane. The water volume which does not pass through the membrane, the reject stream, will contain dissolved materials including radionuclides. The needed output from the RO system is required for design. The actual output of the RO system may not necessarily depend on the conversion rate of radionuclides but, it may, as in the case of water with a high salt content, depend on the salt concentration. The conversion rate of sodium chloride, about 70 percent, is less than that for radionuclides. Hence, if the RO system is designed to remove sodium chloride, radionuclides are also removed. The volume of water which passes through the membrane is:

(volume, applied) x
(conversion rate).

For example, if 100,000 gallons per day of brackish water were applied to a membrane, the volume which would pass through (permeate) would then be:

(100,000 gpd) (0.70) =
70,000 gallons.

Step 2 - Calculation of Reject Volumes and Concentration

In the operation of an RO system, dissolved material which does not pass through the membrane will be present in the reject stream.

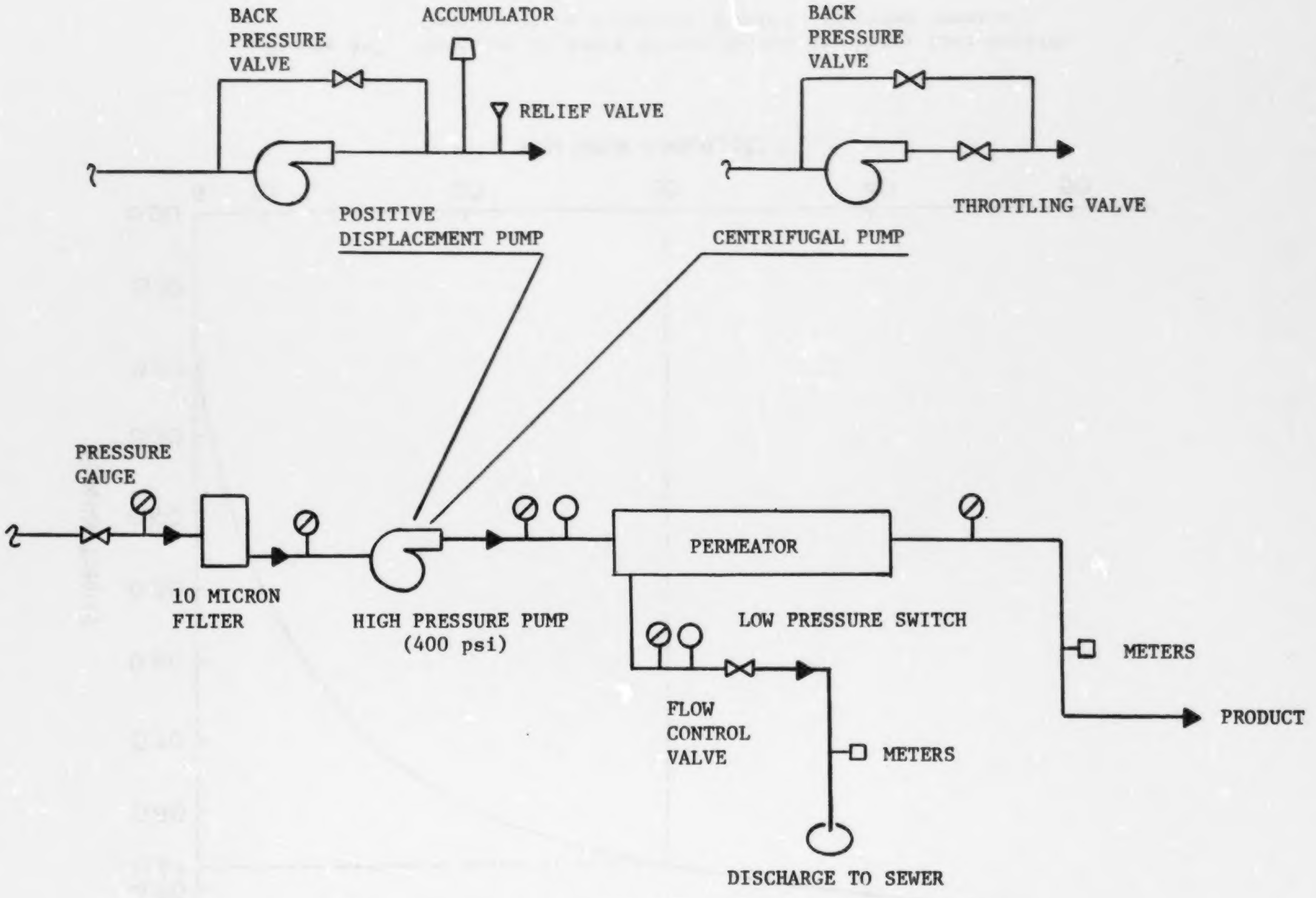
BACK PRESSURE VALVE
ACCUMULATOR
RELIEF VALVE
BACK PRESSURE VALVE
THROTTLING VALVE
POSITIVE DISPLACEMENT PUMP
CENTRIFUGAL PUMP
PRESSURE GAUGE
10 MICRON FILTER
HIGH PRESSURE PUMP (400 psi)
PERMEATOR
LOW PRESSURE SWITCH
METERS
PRODUCT
FLOW CONTROL VALVE
METERS
DISCHARGE TO SEWER

Figure 4-2. Typical RO System Design

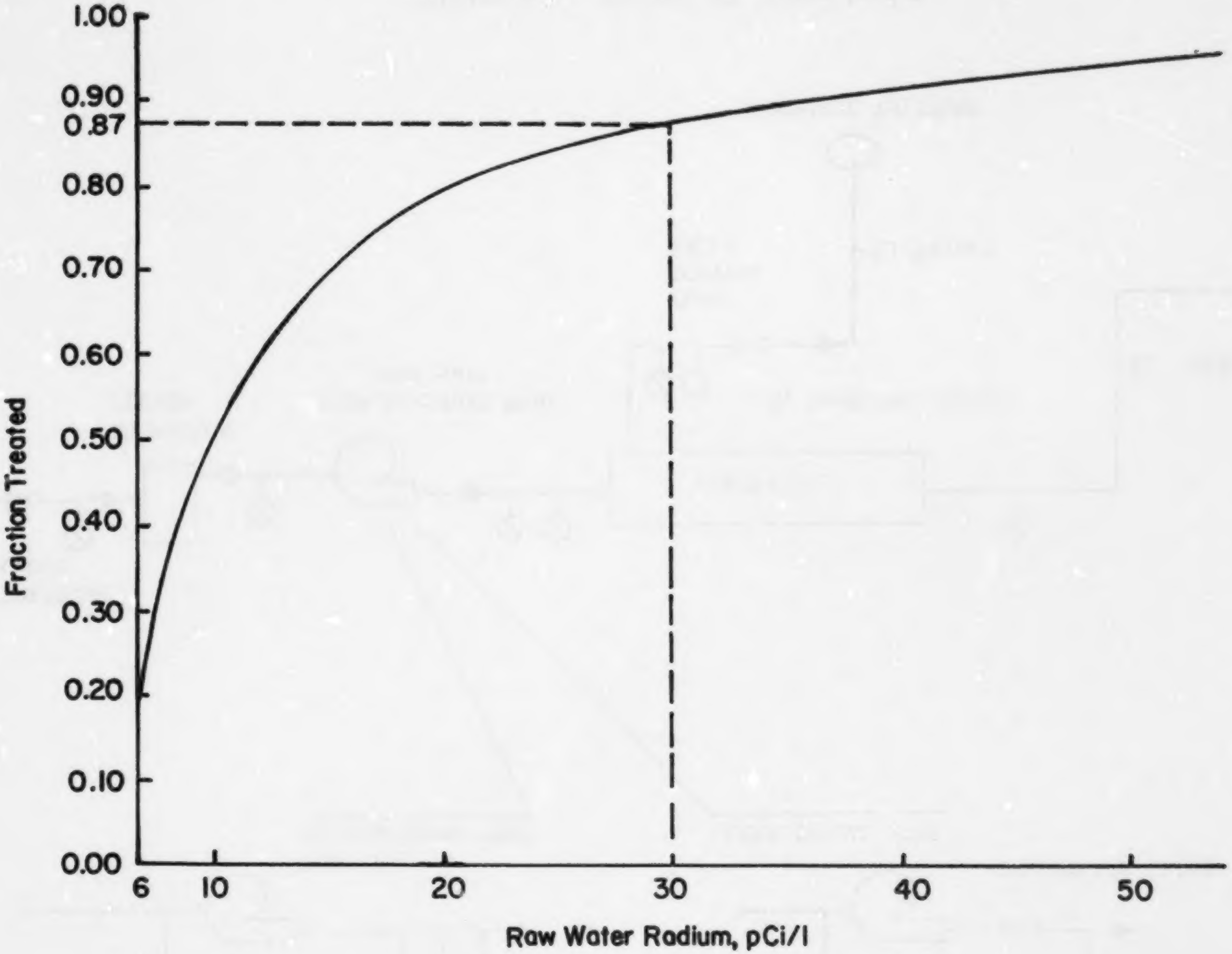

Figure 4-3. Fraction of Water Needed Versus Raw Water Radionuclide Concentration to Obtain 5 PiC/1 - Reverse Osmosis

The concentration of compounds in the reject stream can be calculated using the following expression:

$$\frac{\text{(concentration in water applied to the membrane)}}{\text{(1-conversion rate)}} = \text{concentration in reject stream}$$

For example, if 100,000 gpd were applied to an RO membrane, and the sodium chloride concentration in this water was 1,000 mg/l, then assuming a 70 percent conversion rate for sodium chloride:

$$\frac{(1{,}000)}{(1-.70)} = x$$

$$x = 3{,}333 \text{ mg/l}$$

The volume of the reject stream can be determined using the following equation:

(Volume applied to membrane)
(1-conversion rate)

Example: (100,000)(1-0.70) = 30,000 gallons.

Hence, 30,000 gallons per day of a stream containing 3,333 mg/l of sodium chloride would require disposal. The radium concentration of this stream is dependent upon the rejection rate and the raw water radium concentration. If the raw water contained 30 pCi/l radium, and radium rejection were 95 percent, then the radium concentration of this stream is calculated as follows:

= (100,000 gallons)
(3.785 liters/gallon)
(30 pCi/l)(0.95)

= 10,787,250 pCi removed.

In 30,000 gallons, the concentration is then:

$$\frac{10{,}787{,}250 \text{ pCi}}{(30{,}000 \text{ gal})(3.785 \text{ liters/gal})}$$

= 95 Pci/l in the 30,000 gallons

Posttreatment

Following RO treatment the water will be extremely soft since both calcium and magnesium are removed in the RO process. The water will also contain carbon dioxide (CO_2) as a result of acid pretreatment to prevent $CaCO_3$ incrustation on the membrane. This CO_2 will make the water acidic.

To remove carbon dioxide, an aerator, termed a decarbonator, is used to strip the carbon dioxide gas from the water and consequently raise the water pH. Further pH adjustment using soda ash may be needed after decarbonation. Corrosion inhibitors may also be necessary to protect pipes in the RO unit and in the distribution system.

V. WASTE RESIDUE HANDLING

Each treatment process for removing radionuclides from a raw water source generates a waste stream of some sort. These wastes must be disposed of in an environmentally acceptable manner. The purpose of this section is to describe the characteristics of each waste stream, to identify the available options for disposal of each type waste, and to summarize applicable Federal Regulations pertaining to disposal of such wastes.

Most of the information presented is based on the experience of water treatment plants throughout the U. S. that treat water containing radium. Radium is the only naturally occurring radionuclide for which a maximum contaminant level exists under the national Interim Primary Drinking Water Regulations. Radium is also the radionuclide which occurs most often at elevated levels in natural waters in the U. S serving community water systems. (There is some indication radium occurs relatively frequently in private individual water supplies.)

Uranium, the second most frequently occurring natural radionuclide, has generally been shown to be present at levels of activity equal to or less than that of radium. Although there are little or no data on the radioactivity of uranium in water treatment plant waste streams, the levels which may exist are likely to be close enough to those of radium for the discussion presented in this section to be appropriate.

The level of radiation present in all the waste streams described below is several orders of magnitude below levels which would identify them as low-level nuclear wastes, subject to regulation by the Nuclear Regulatory Commission. In fact, there are no federal regulations which regulate the disposal of these waste streams based on their radioactivity. Other characteristics, such as the total suspended solids, total dissolved solids, or salinity of these waste streams are generally the primary characteristics which require special consideration for their disposal.

State and local regulations regarding handling of such residues should always be reviewed and complied with prior to deciding on any treatment alternative for radionuclide removal.

In the absence of site-specific data, residues should always be measured to verify that maximum radioactivity does not exceed regulatory acceptable levels.

Personnel responsible for selection of a treatment alternative for radionuclide removal must inform themselves of all pertinent regulations and select among the various waste stream disposal alternatives based on the practicality and cost of each alternative. Site specific variables such as land availability, local geology, distance to nearest landfill or sanitary sewer connection, preclude accurate estimation of disposal costs. For further information on selection of a sludge disposal alternative, refer to EPA Publication 600/2-77-073, Costs of Radium Removal from Potable Water Supplies, April 1977.

CHARACTERISTICS OF WASTE STREAMS GENERATED BY WATER TREATMENT PROCESSES FOR RADIONUCLIDE REMOVAL

Lime-soda softening sludge consists primarily of calcium carbonate and magnesium hydroxide solids precipitated by the treatment process. Insoluble heavy metals in trace concentrations, including radium, are also contained in the sludge. Unthickened sludge ranges from 2 to 15 percent solids. This sludge can be dewatered relatively easily compared to alum or iron salt sludges.

When the filters of a lime-soda softening plant are backwashed, a relatively dilute waste stream results. On the average, backwash water volume comprises 2 to 4 percent of the total finished product. Backwash water is contaminated by the fine particles trapped by the plants filters.

The concentrated salt solution used to regenerate an ion-exchange resin bed, backwash water, and resin rinse water comprise the waste stream of an ion-exchange system. Typically, waste stream volume will be 2 to 5 percent of the finished water volume.

Waste products from the brine and rinse cycle are composed primarily of chlorides of calcium and magnesium and the excess salt necessary for regeneration. Total solids in a composite sample may vary from an average concentration ranging from 50,000 to 100,000 mg/l to a maximum of 200,000 mg/l.

Reverse osmosis reject water is generated continuously during treatment, and typically equals 20 to 50 percent of the finished water volume. Contaminants in the reject stream include those in the raw water, however, the contaminant concentration (including radium) may be 2 to 5 times higher.

Table 5-1 presents an estimate of the radioactivity and quantity of treatment waste residues for lime-soda softening, ion exchange, and reverse osmosis processes. These data are based on the experience of numerous water treatment plants in the U. S. which treat their source waters for radium removal.

DISPOSAL ALTERNATIVES FOR LIME-SODA SOFTENING SLUDGE

Alternatives for disposal of lime-soda softening sludge, summarized in Table 5-2, are many and varied. Alternatives which involve land storage or disposal may come under the jurisdiction of state or local authority. Direct discharge to a navigable waterway requires an NPDES permit. Discharge to a sanitary sewer is usually controlled by local ordinance.

DISPOSAL ALTERNATIVES FOR LIME-SODA SOFTENING BACKWASH WATERS

Lime-soda softening backwash waters are much lower in suspended solids and radioactivity than lime-soda softening sludges. Current practice at most plants is to collect the backwash waters

TABLE 5-1

ESTIMATED RADIOACTIVITY AND QUANTITY OF WATER TREATMENT WASTE RESIDUES

Residue	Radioactivity Levels as a Function of Radioactivity of Raw Water, pCi/l			Quantity of Waste Stream as a Function of TDS of Raw Water, mg/l		
	15	30	50	400	1,000	2,000
Lime-Soda Softening Sludge (1)	4,800-20,500 pCi/lbs Dry Sludge	6,900-34,100 pCi/lbs Dry Sludge	10,500-51,400 pCi/lbs Dry Sludge	1,800- 3,200 Dry lbs/MG	3,100- 6,500 Dry lbs/MG	7,600-16,200 Dry lbs/MG
Lime-Soda Backwash Water	40-60 pCi/gal	130-150 pCi/gal	245-265 pCi/gal	20,000-40,000 Gallons/MG	20,000- 40,000 Gallons/MG	20,000-40,000 Gallons/MG
Ion-Exchange Regeneration Brine	490-2,460 pCi/gal	1,140-6,060 pCi/gal	2,270-11,360 pCi/gal	15,000 gal/MG	30,000 gal/MG	75,000 gal/MG
Reverse Osmosis Reject Water	280-760 pCi/gal	450-1,020 pCi/gal	750-1,890 pCi/gal	60,000 gal/MG	60,000-100,000 gal/MG	160,000-260,000 gal/MG

(1) Wet lime soda softening sludges have been reported to contain between 2 to 15 percent solids. After extended periods of storage in a landfill or impoundment, 70 percent solids or greater have been reported. Values reported here for dry solids may be converted to values for wet sludge of different percent solids by multiplying by the appropriate conversion factor.

Source: EPA 600/2-77-073, Costs of Radium Removal from Potable Water Supplies.

TABLE 5-2

SUMMARY OF DISPOSAL ALTERNATIVES FOR LIME-SODA SOFTENING SLUDGE

LAND APPLICATION ALTERNATIVES

- Temporary or permanent lagooning (surface impoundment)
- Sanitary landfill
  - a. with prior temporary lagooning
  - b. with prior mechanical dewatering: vacuum filtration, centrifugation, others
- Other natural or man-made depressions (all with some dewatering before transportation)
  - a. strip mine areas
  - b. borrow pits and quarries
- Application on farmland for soil neutralization (with or without dewatering)

DISCHARGE ALTERNATIVES

- Direct discharge to surface receiving water
- Underground injection (aquifer recharge)
- Discharge to sanitary sewer

USE ALTERNATIVES

- Road stabilization
- Calcination and reuse in water plant

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in a tank or lagoon in order to settle most of the solids. The settled backwash water is then either returned to the head of the plant for treatent or discharged, either to a sanitary sewer or navigable waterway. The discharge alternatives are usually regulated by NPDES (navigable waterway) or local ordinance (sanitary sewer).

DISPOSAL ALTERNATIVES FOR ION-EXCHANGE BRINES

One of the problems created by sodium cycle ion exchange softening is the disposal of spent brine from the regeneration cycle. In view of increasing water pollution control requirements, these high salinity waters may face severe limits on discharge.

Table 5-3 summarizes the available options for disposal of ion-exchange brines. As always, direct discharge options to waterways require an NPDES permit. Disposal in the ocean, if possible, is a particularly attractive alternative. Discharge to a sanitary sewer may be difficult due to the high salinity of the waste unless the overall volume discharged is small compared to the capacity of the treatment plant. Underground injection of waste brines is regulated by the Underground Injection Control provisions of the Safe Drinking Water Act; Federal and/or state permits will probably be required.

REVERSE OSMOSIS WASTE

Dissolved solids rejected by the membrane in a reverse osmosis unit flow continuously from the unit in a concentrated waste stream. Because the waste is produced continuously in large volumes and no major additions of chemicals are required, waste strength (2 to 5 times the raw water concentration) is lower than ion-exchange brine strength. Discharge to a sanitary sewer may be feasible for reverse osmosis waste. Other alternatives, including storage, use/recovery and disposal, are similar to ion-exchange brine.

APPLICABLE FEDERAL REGULATIONS

Federal regulations which apply to the disposal of water treatment plant waste residue into navigable waters, by deep well injection, and on land are as follows:

1. Navigable Waters--Water treatment waste residues discharged into navigable waterways are regulated by authority of the Clean Water Act under the National Pollutant Discharge Elimination System (NPDES) 40 CFR 125, 129, 133, and Subchapter N. State and/or local regulatory agencies usually retain regulatory jurisdiction over such discharge through enforcement of applicable water quality regulations.

   New or existing water plants which discharge water residues to navigable waters must obtain required permits from the local, state, and/or EPA region in which they are located. Generally, low-level radionuclide content waste residues are not regulated differently than other water treatment plant discharges. It is suggested that the state or local regulatory agency be contacted for further information.

2. Well Injection--Waste residue which is injected underground is regulated under authority of the Underground Injection Control (UIC) Program pursuant to Part C of the Safe Drinking Water Act and Subsequent Regulations (40 CFR 124, 144, 145, 146). Disposal by injection must be accomplished in accordance with state, and/or EPA regulations.

3. Land Disposal--Land disposal of water plant waste residues is not specifically regulated under authority of the Resource Conservation and Recovery Act's Hazardous Waste Management Program, 40 CFR 260-266.

TABLE 5-3

ALTERNATIVES FOR DISPOSAL OF ION-EXCHANGE BRINES

DISCHARGE ALTERNATIVES

- Sanitary Sewer
- Receiving Waters
    - Streams
    - Ocean

DISPOSAL ALTERNATIVES

- Injection into deep aquifers
- Disposal to oil well fields

STORAGE/USE ALTERNATIVES

- Evaporation lagoons
- Sale of recovered salt

Radioactivity is not among the characteristics which determine whether or not a solid waste will be considered hazardous. Solid wastes are deemed hazardous if they are specifically listed in the regulation under 40 CFR 261.4 or if they exhibit the characteristics of ignitability, corrosivity, reactivity, and/or EP toxicity as defined in Sections 261.20 to 24 of 40 CFR.

Radioactive wastes defined as source, special nuclear, or by-product materials are specifically excluded from regulation in Section 261.4. This exclusion does not include natural radionuclides normally found in potable water treatment sludges and brines.

Disposal of water treatment residues containing radioactive components can be regulated under Nuclear Regulatory Commission (NRC) regulations in certain circumstances. For example, if the radioactivity is due to naturally occurring uranium and has a concentration greater than 0.05 percent, it can be regulated under 10 CFR Part 30. Similarly, if radioactivity results from a by-product of a commercial process and is in excess of approximately 10^{-4} microCurie/ml, the material can also be regulated under 10 CFR Part 30.

However, radioactivity due to naturally occurring radium, such as that in the sludges and brines in question, is not subject to NRC regulation.

Landfilling and application of waste treatment residues are generally under the jurisdiction of state and local regulatory agencies who should be consulted to determine regulatory requirements prior to selection of a particular alternative.

VI. COST ESTIMATING PROCEDURES AND FUNDING SOURCES

This section provides a summary of the kinds of costs that are likely to be encountered in any treatment facility construction project and outlines a procedure to estimate costs associated with treatment for radionuclide removal. It also summarizes some estimated construction and operating cost projections which have been made for radionuclide removal systems.

Costs depend largely on site-specific conditions which may change over a period of time. The cost estimates in this report were based on assumptions made when the cost curves were developed (1976-1978). In this regard, other projects are currently in progress to refine and improve the accuracy of cost estimating procedures. As these projects are completed they should be consulted for more accurate cost estimation procedures.

The total cost estimate for a water treatment facility is generally the sum of the costs associated with two major categories: (1) Construction Costs, and (2) Operation and Maintenance Costs. Each of these major cost categories is composed of individual costs for a number of components. To arrive at a total cost estimate for a given facility, the component costs are evaluated, adjusted as necessary for site-specific considerations and inflation, then summed. Costs can be expressed many ways: annual cost, and cost per thousand gallons treated are two of the most common. The latter can be used directly to estimate the effect the project will have on the individual consumer's water bill. However, cost curves are generally most useful for comparing relative costs of treatment alternatives and for approximating the general cost level to be expected for a proposed treatment system.

CONSTRUCTION COSTS

Introduction

Whenever treatment costs are determined, whether from a published report or a vendor's estimate, it is extremely important to establish exactly what components and processes the cost estimate includes. Different cost estimates based on different basic assumptions (such as water quality) and different components (such as housing) have in the past resulted in many misunderstandings. In addition, if the costs are taken from a report, it is important to be sure they apply to the size category of your system. Once this has been ensured, cost comparisons between alternatives can be made using the process outlined above. To illustrate this procedure, the cost information developed by the EPA Municipal Environmental Research Laboratory (presented in a 4-volume report titled: Estimating Water Treatment Costs (EPA-600/2-79-162) can be used. This report presents cost curves for 99 unit processes useful for removing contaminants covered by the NIPDWR.

The construction cost curves presented in this section were developed by using equipment cost data supplied by manufacturers, cost data from actual plant construction, published data, and estimating techniques from Richardson Engineering Services Process Plant Construction Estimating Standards, Mean's Building Construction Cost Data, and the Dodge Guide for Estimating Public Works Construction Costs. The construction cost curves were then checked and verified by an engineering consulting firm.

The construction cost for a treatment facility was developed by determining and then aggregating the cost of eight principal components. The components are categorized to facilitate accurate cost updating, which is discussed later in this report. The categorization will also be useful where costs are being adjusted for site-specific, geographic, and other special conditions. The eight categories include the following general items:

Excavation and Site Work. This category includes work related only to the applicable process and does not include any general site work such as sidewalks, roads, driveways, or landscaping which should be itemized separately.

Manufactured Equipment. This category includes estimated purchase costs of pumps, process equipment, specific purpose controls, and other items that are factory made and sold with equipment.

Concrete. This category includes the delivered cost of ready-mix concrete and concrete-forming materials.

Steel. This category includes reinforcing steel for concrete and miscellaneous steel not included within the manufactured equipment category.

Labor. The labor associated with installing manufactured equipment, and piping and valves, constructing concrete forms, and placing concrete and reinforcing steel are included in this category.

Pipe and Valves. Cast iron pipe, steel pipe, valves, and fittings have been combined into a single category. The purchase price of pipe, valves, fittings, and associated support devices are included within this category.

Electrical Equipment and Instrumentation. The cost of process electrical equipment, wiring, and general instrumentation associated with the process equipment is included in this category.

Housing. In lieu of segregating building costs into several components, this category represents all material and labor costs associated with the building, including heating, ventilating, air conditioning, lighting normal convenience outlets, and the slab and foundation.

The construction cost curves presented in this document are the sum of the above cost components, subcontractor overhead and profit, and a 15 percent contingency. These costs are based on October 1978 dollars and can be updated by using the Engineering News Record (ENR) Construction

Cost Index (CCI), or Building Cost Index (BCI). Current indices are also published weekly in McGraw-Hills' ENR Journal. Historical indices are periodically tabulated in the Journal.

The following equation can be used to update construction costs:

$$\text{Updated Cost} = \text{Cost from Curve} \times \frac{\text{(Current ENR Construction Cost Index (CCI)}}{\text{(ENR CCI when costs were determined)}}$$

The construction cost curves used in this document are based on October 1978 costs when the ENR CCI was 265.38. The ENR CCI for June 1982 was 352.92. Thus, to update construction cost estimates given in this document to June 1982 costs, the given costs must be multiplied by the ratio of: $\frac{352.92}{265.38}$. Note that the ENR CCI is the average of the 20-city average construction cost index--there is wide variation between individual cities and regions of the U. S. For example, the August 1982 index varied from a low of 274 to a high of 360 among the 20 cities, about a 31 percent difference. As a result, updated cost figures using this adjustment may tend to over or underestimate costs, depending on construction costs in the locality of interest. More sophisticated cost estimating techniques are available; they are described in this section.

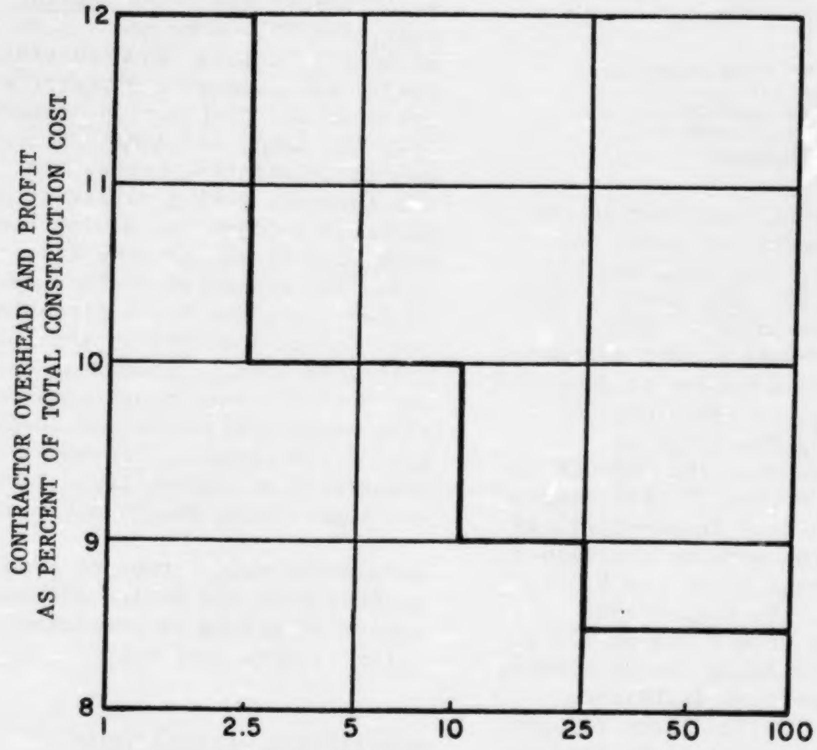
To estimate total construction costs, several site-specific costs must be added to the construction cost obtained from the curve: (1) special sitework, landscaping, roads, and interface piping between processes, (2) special subsurface considerations, and (3) standby power. The special costs vary widely, depending on the site, the design engineer's preference, and regulatory agency requirements. Addition of these special costs to the aggregate cost of the unit processes gives the total construction cost.

To arrive at the total capital cost, the following costs must be added to the total construction cost: (1) general contractor's overhead and profit, (2) engineering, (3) land, (4) legal, fiscal and administrative costs, and (5) interest during construction. Curves for these costs with the exception of engineering and land, are presented in Figures 6-1 to 6-5. A curve for engineering cost is not included as the cost will vary widely, depending on the need for preliminry studies, time delays, the size and complexity of the project, and any construction related inspection and engineering design activities.

An example calculation of total capital cost for an ion-exchange treatment system is presented later in this section.

Annualizing Capital Costs

To determine the true total yearly cost of owning, maintaining, and operating a radionuclide removal system, all costs must be stated on an annualized basis. Operating and maintenance costs are normally stated on this basis. Capital costs can be annualized as a series of equal payments needed to recover the initial expenditure over the life of the treatment system, plus interest costs.



TOTAL CONSTRUCTION COSTS, million dollars

Figure 6-1. General Contractor's Overhead and Fee Percentage Versus Total Construction Cost

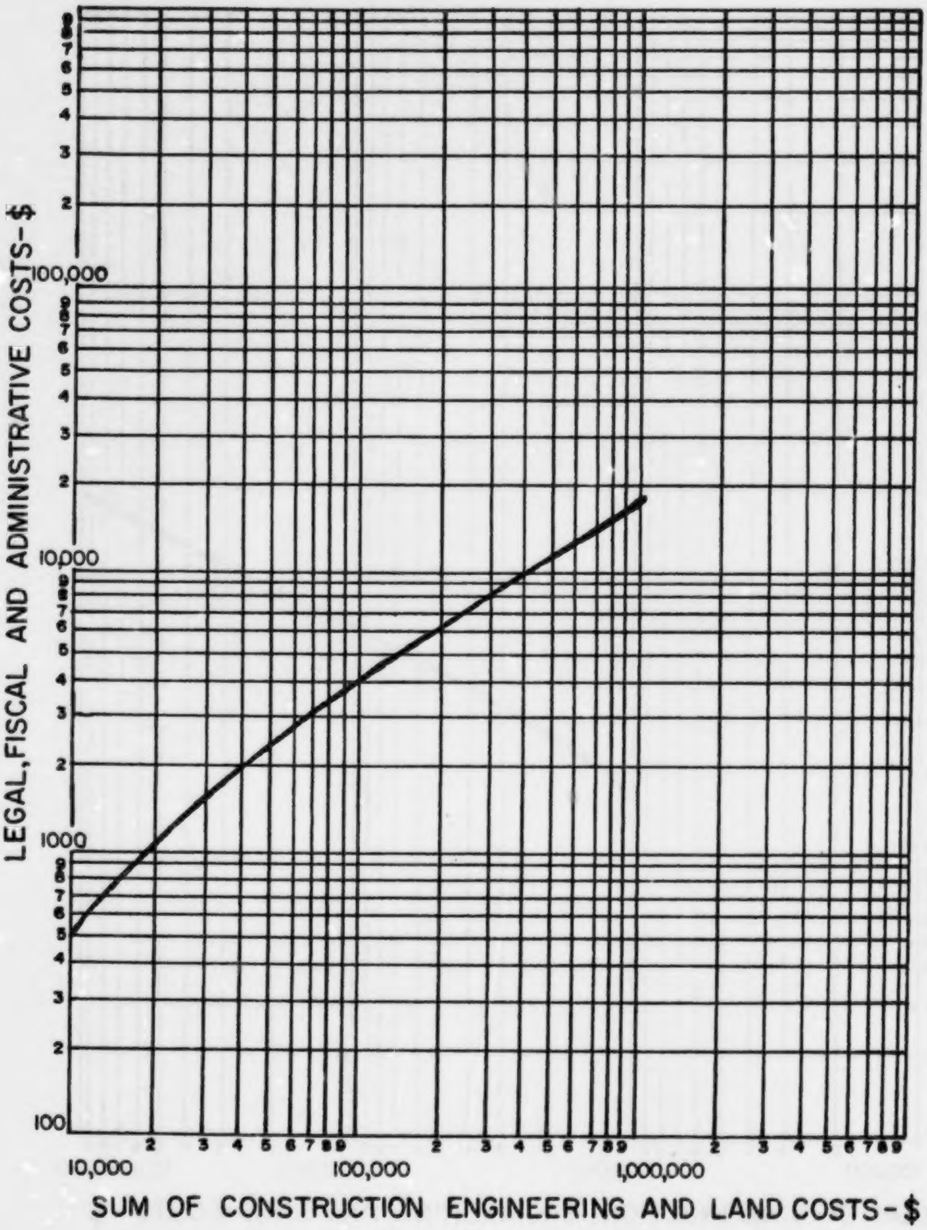


Figure 6-2. Legal, Fiscal, and Administrative Costs for Projects Less than $1 Million

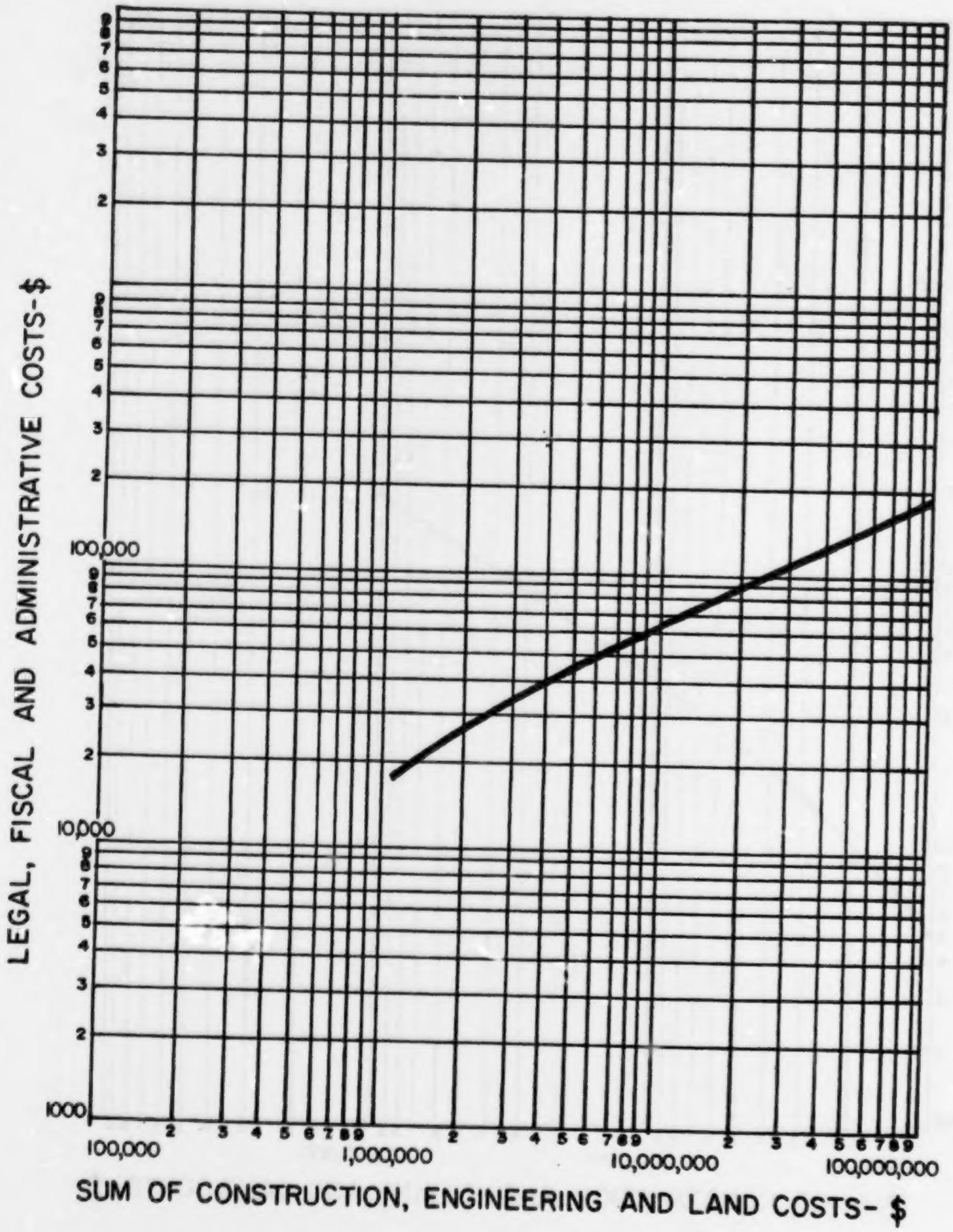


Figure 6-3. Legal, Fiscal, and Administrative Costs for Projects Greater than $1 Million

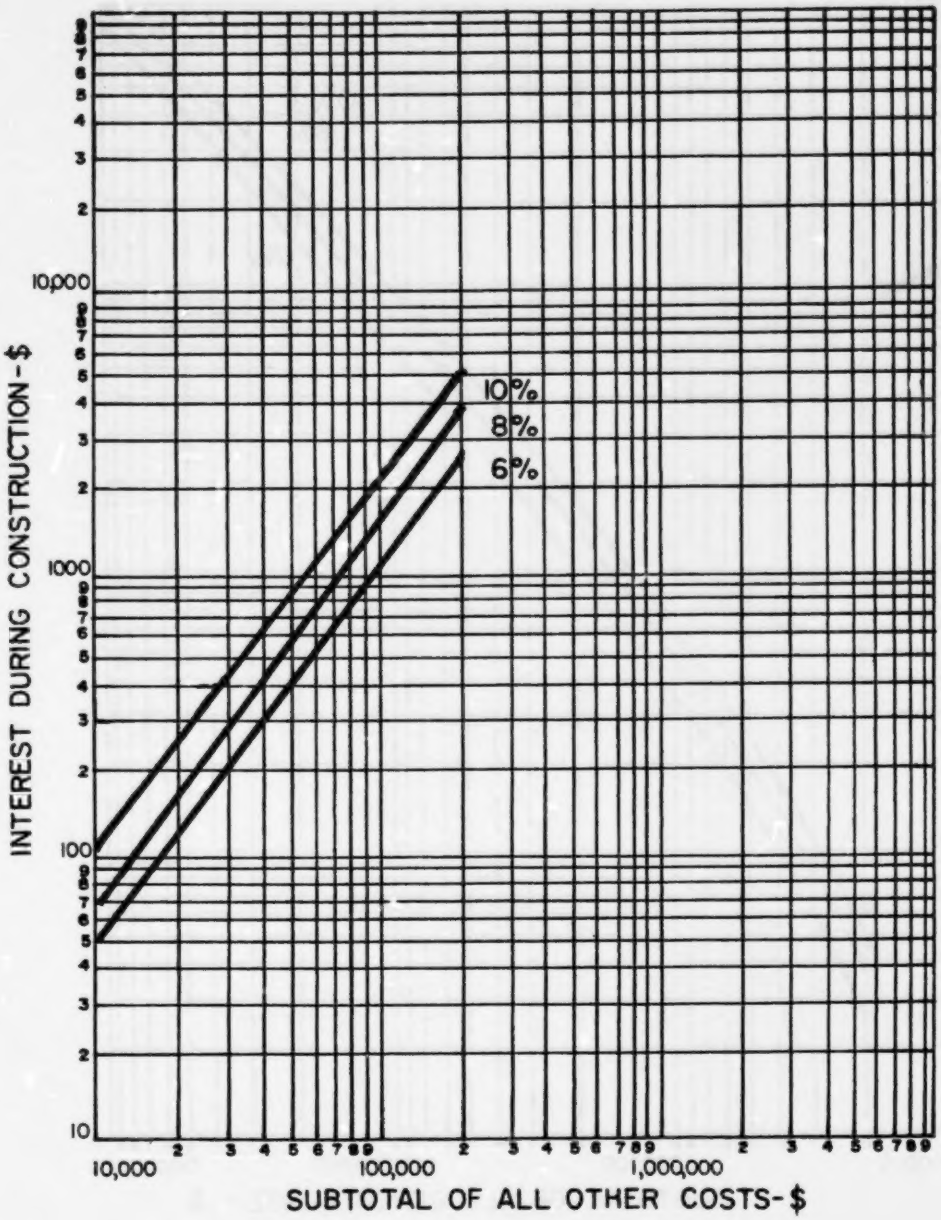


Figure 6-4. Interest During Construction for Projects Less than $200,000

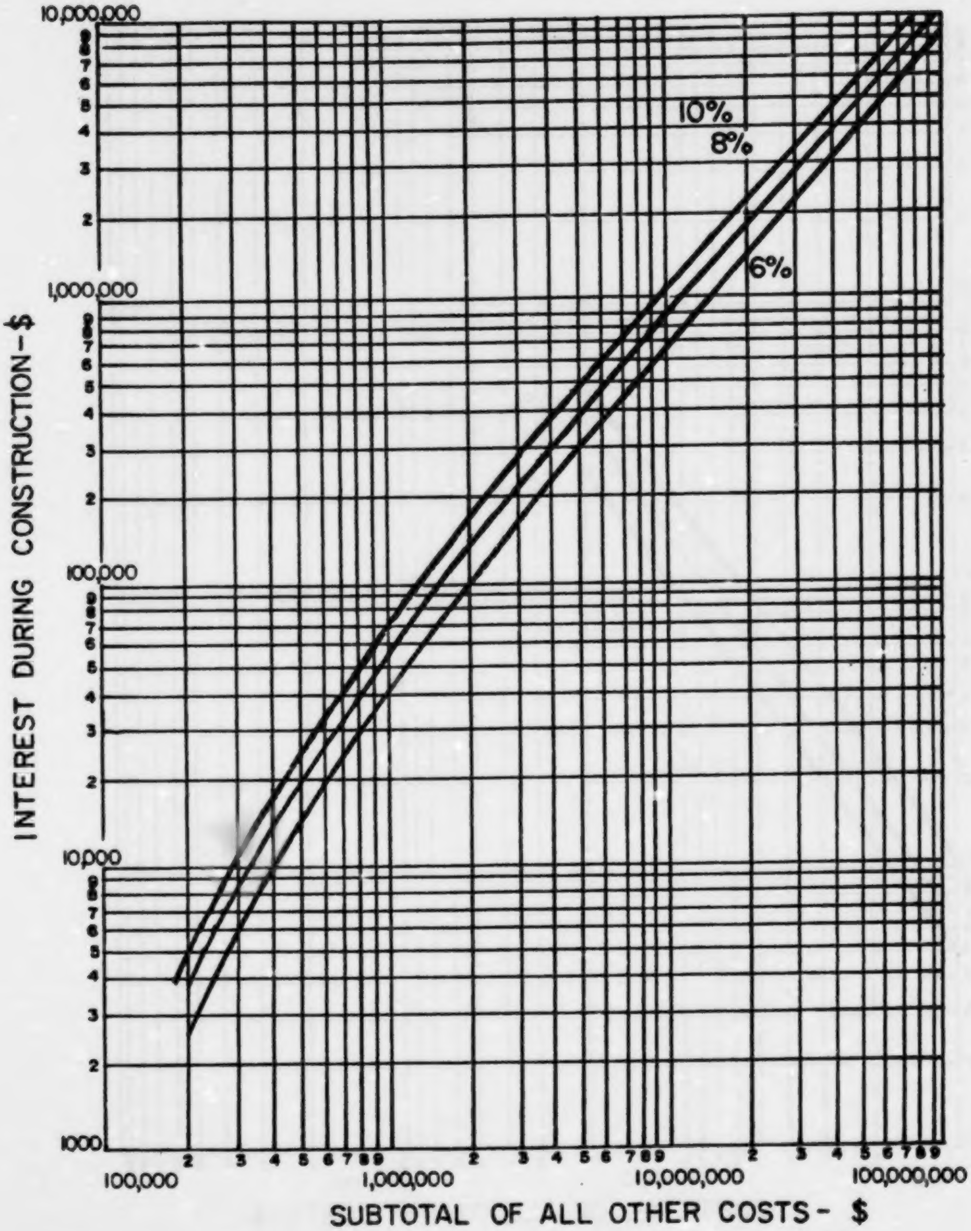


Figure 6-5. Interest During Construction for Projects Greater than $200,000

Annual payment needed to recover the initial capital cost can be determined by multiplying the lump sum amount times a capital recovery factor (CRF) as follows:

Annualized Construction Cost = Construction Cost x CRF

The CRF is a function of the construction loan interest rate (i), and the life of the treatment system (n):

$$\text{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1}$$

Many economics handbooks provide tables of CRF values corresponding to various combinations of interest and project life. Table 6-1 is an abbreviated example of this type table. The cost example in this section shows how tables can be used to find the annual cost equivalent of a proposed system's capital cost estimate.

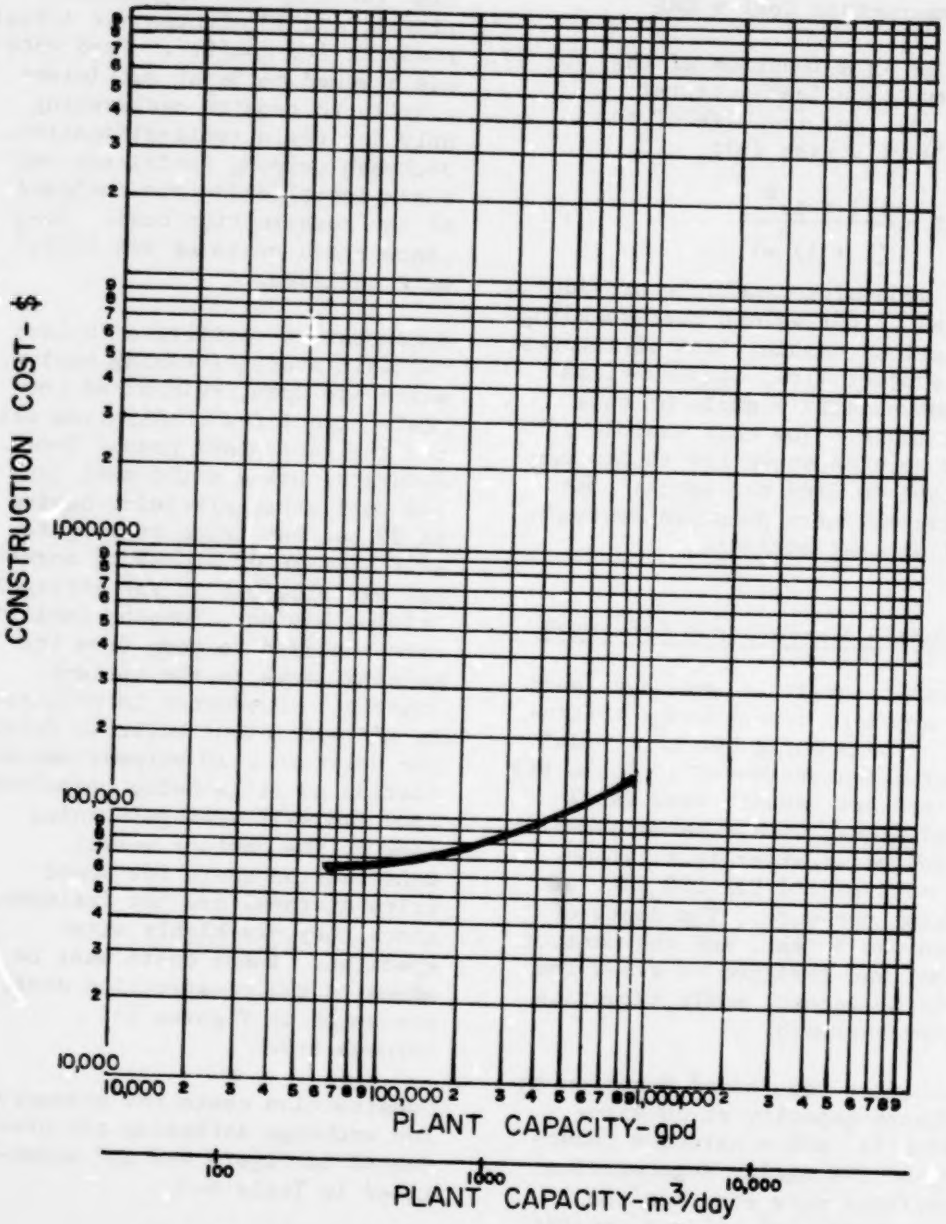
Example - Ion-Exchange Softening

Construction costs were developed for pressure ion-exchange softening systems using the conceptual information presented in Table 6-2. The contact vessels were fabricated steel, with a baked phenolic lining added after fabrication and constructed for 100 psi working pressure. The depth of resin was 6 feet, and the contact vessel was designed to allow for up to 80-percent media expansion during backwash.

Facilities were sized based on an exchange capacity of 20 kilograins/ft^3 and a hardness reduction of 300 mg/l. Regeneration facilities were sized on the basis of 150 bed volumes treated before regeneration and a regenerant requirement of 0.275 lb of sodium chloride per kilograin of exchange capacity. The total regeneration time required is 50 minutes. Of this time, 10 minutes are for backwash, 20 minutes are regeneration brine contact time (brining and displacement rinse), and 20 minutes are a fast rinse at 1.5 gpm/ft^3. Feed water was assumed to be of sufficient clarity to require backwashing only for resin reclassification. Backwash pumping facilities and resin installation are included in the construction cost. In-place resin costs of \$45.00/ft^3 were utilized.

Regeneration facilities include two salt storage/brining basins, which are open, reinforced concrete structures constructed with the top foot above ground level. Saturated brine withdrawal from the salt storage/brining basins is 25 percent brine by weight. A salt storage of 4 days of normal use was provided in the storage/brining basins. Pumping facilities were included to pump from the brining tanks to the contact vessels. An eductor is utilized to add sufficient water to dilute the brine to a 10 percent concentration as it is being transferred from the salt storage/brining tank to the contact vessel. Construction costs for spent brine disposal are not included, since they are highly site-specific. These costs must be added to the construction costs presented in Figures 6-1 through 6-5.

Construction costs for pressure ion exchange softening are presented in Figure 6-6 and summarized in Table 6-3.



Source: EPA-600/2-79-162

Figure 6-6. Construction Cost for Pressure Ion-Exchange Softening

TABLE 6-1

CAPITAL RECOVERY FACTORS FOR SOME COMBINATIONS OF INTEREST (i) AND PROJECT LIFE (n)

	Capital Recovery Facts					
n years	6%	7%	8%	9%	10%	12%
5	0.237396	0.243891	0.250456	0.257092	0.263797	0.277410
10	0.135868	0.142378	0.149029	0.155820	0.162745	0.176984
15	0.102963	0.109295	0.116830	0.124059	0.131474	0.146824
20	0.087185	0.094393	0.101852	0.109546	0.117410	0.133879
25	0.078227	0.085811	0.093679	0.101806	0.110168	0.127500

TABLE 6-2

CONCEPTUAL DESIGN FOR ION-EXCHANGE SOFTENING

Plant Capacity (gpd)	Number of Contactors	Diameter of Contactors(ft)	Housing (ft^2)	Total Salt Storage/Brining Capacity (ft^3)
70,000	2	2	132	110
280,000	2	4	210	435
440,000	2	5	255	680

Source: EPA-600/2-79-162.

TABLE 6-3

CONSTRUCTION COST FOR ION-EXCHANGE SOFTENING
(1978 Dollars)

Cost Category	Plant Capacity (gpd) 70,000	280,000	440,000
Excavation and Sitework	$ 320	$ 640	$ 800
Manufactured Equipment:			
Equipment	11,360	16,000	18,580
Resin	1,700	6,790	10,600
Concrete	700	1,400	1,750
Steel	1,080	2,170	2,710
Labor	5,220	7,430	8,800
Pipe and Valves	9,550	12,340	13,500
Electrical and Instrumentation	18,390	21,600	23,070
Housing	7,600	8,900	9,800
SUBTOTAL	$55,920	$77,270	$ 89,610
Miscellaneous and Contingency	8,390	11,590	$ 13,440
TOTAL	$64,310	$88,860	$103,050

Source: EPA-600/2-79-162.

Construction costs for other radionuclide control alternatives such as reverse osmosis or lime-soda softening can be estimated in a manner similar to that presented above.

OPERATION AND MAINTENANCE COSTS

To obtain a total operation and maintenance (O&M) cost, the individual costs for energy (process and building heating), maintenance material, and labor must be determined and summed.

Total operation and maintenance costs from a reference document or previous contractor's estimate can be updated and adjusted to local conditions by updating and adjusting cost components, energy, labor, and maintenance material. Energy and labor requirements are generally provided in kilowatts per year and hours per year, respectively. Available cost curves are developed by multiplying these requirements by the cost of power and labor, respectively. To update such a curve, the cost per year is multiplied by the ratio of current energy or labor costs divided by the respective unit cost used to develop the original cost curve. For example, assume a particular cost curve was developed assuming energy costs were $0.03 per kilowatt hour. If electricity now costs $0.05 per kilowatt hour, the current annual energy cost for a given facility can be determined by multiplying the annual cost from the graph by the rates of: $\frac{0.05}{0.03}$. An example of this technique is provided. Likewise, maintenance material costs are related to the Producer Price Index (PPI) for Finished Goods. To update this component, the PPI at the time the original cost estimates were made must be known. Then the new annual cost is determined by multiplying the cost from the graph by the ratio of the new PPI divided by the PPI at the time the graph was prepared. The technique is also demonstrated in the example at the end of this section.

Example - Ion-Exchange Softening

Operation and maintenance costs were also estimated and are presented in this section. The basis and assumptions used are outlined in the following subsection.

Ion-Exchange Operation and Maintenance Cost

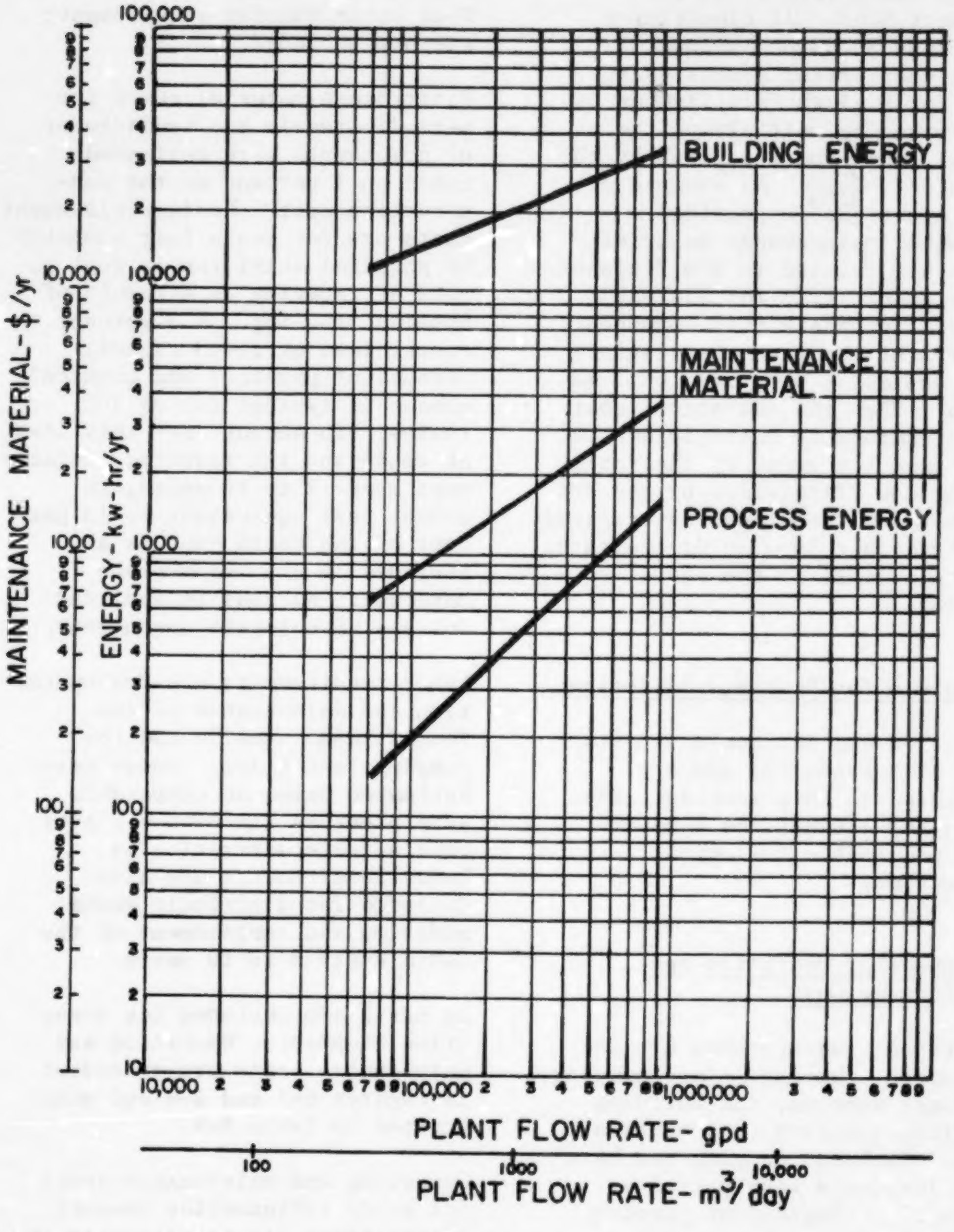
Electrical requirements are for regenerant pumping, rinse pumping, backwash pumping, and building heating, lighting, and ventilation. Backwash pumping was based on a 10-minute wash period at 8 gpm/ft^2. Regenerant pumping was based on a regenerant rate of 0.7 gal/min/ft^3 of resin and a regeneration time of 20 minutes. Fast-rinse pumping was based on a 20-minute rinse at a rate of 30 gal/ft^3 of media. All pumping was assumed to be against a 25-foot total dynamic head (TDH). Feed water pumping requirements are not included.

Maintenance material costs for periodic repair and replacement of components were estimated based on 1 percent of the construction cost. Resin replacement costs are for resin lost annually by physical attrition as well as loss of capacity as a result of chemical fouling. A 3 percent annual loss of resin capacity because of physical and chemical causes is typical for cation resins. To account for this loss of resin and the required replacement every 8 to 10 years, an annual cost equivalent to 13 percent of the resin cost is also included in the maintenance material. No cost is included for sodium chloride regenerant.

Labor requirements are for operation and maintenance of the ion-exchange vessels and the pumping facilities. Hours were estimated based on comparable size pressure filtration plants that operate automatically. Labor requirements are also included for a periodic media addition and replacement of the media every 8 to 10 years.

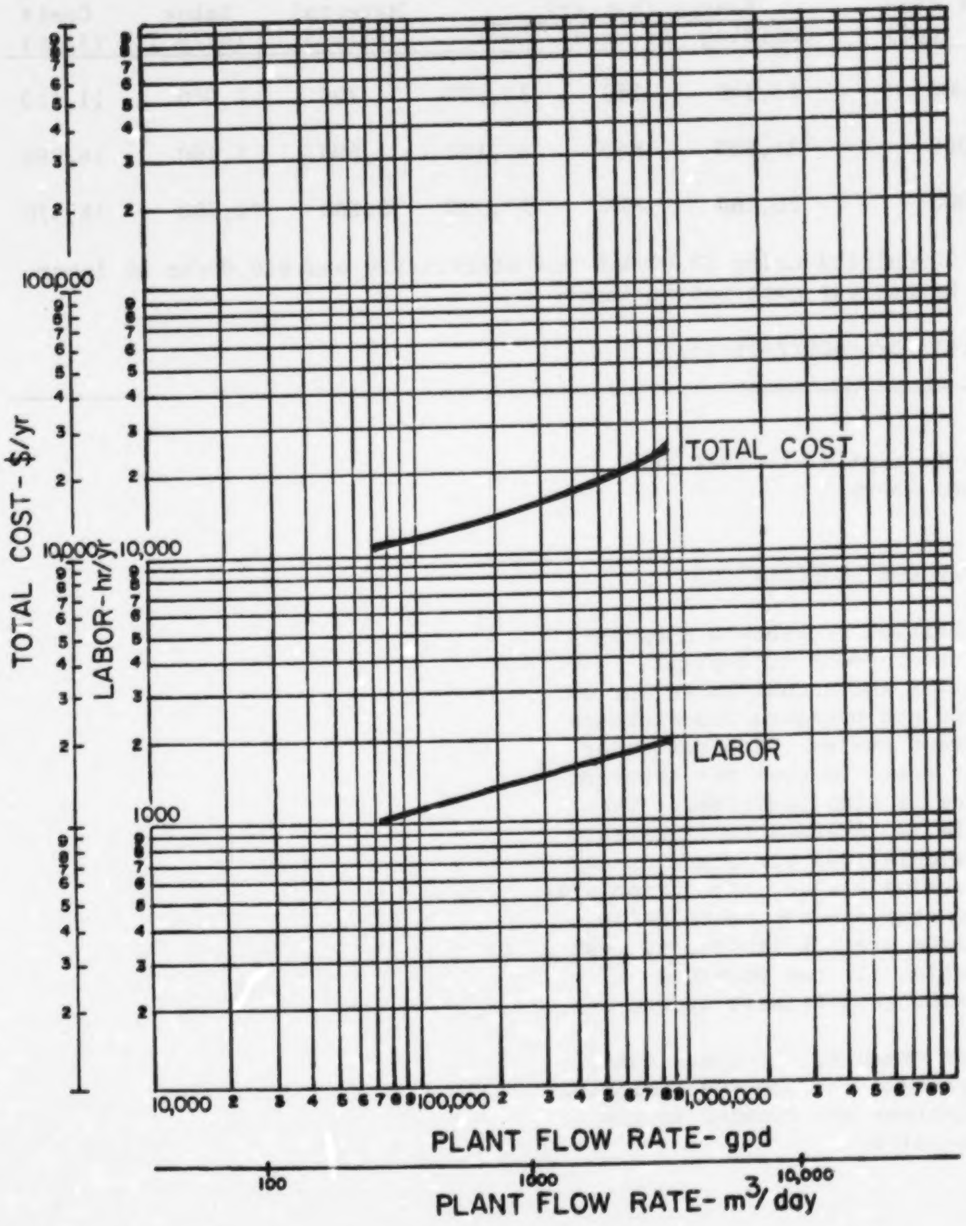
No costs are included for spent brine disposal. Operation and maintenance costs are presented in Figures 6-7 and 6-8 and summarized in Table 6-4.

Operating and maintenance costs for other radionuclide removal alternatives can be estimated in



Source: EPA-600-2-79-162.

Figure 6-7. Operation and Maintenance Requirements for Pressure Ion-Exchange Softening - Building Energy, Process Energy, and Maintenance Material



Source: EPA-600-2-79-162.

Figure 6-8. Operation and Maintenance Requirements for Pressure Ion-Exchange Softening - Labor and Total Cost

TABLE 6-4

OPERATION AND MAINTENANCE SUMMARY FOR PRESSURE ION-EXCHANGE SOFTENING

Plant Flow Rate (gpd)	Energy (kwh/yr) Building	Energy (kwh/yr) Process	Energy (kwh/yr) Total	Maintenance Material ($/yr)	Labor (hr/yr)	Total Cost* ($/yr)
70,000	13,540	140	13,680	700	1,000	11,110
280,000	21,550	550	22,100	1,600	1,400	16,260
440,000	26,160	870	27,030	2,260	1,500	18,570

* Calculated using $0.03/kwh for electricity and $10.00/hr of labor. Regenerant cost not included.

Source: EPA-600/2-79-162.

a manner similar to that prescribed above.

EXAMPLE COST CALCULATION

This section presents a step-by-step development of capital, operating and annual costs for a 100,000 gpd pressure ion-exchange treatment system. Conversion of annual costs to cost per thousand gallons is also performed. The example is intended to illustrate the calculations performed in any cost estimate; i.e., the principles of the step-by-step calculation technique are not limited to cost estimation for the pressure ion-exchange treatment systems.

In this example, all costs will be expressed in June 1982 dollars. Calculations are rounded to the nearest $100.

EXAMPLE OF COST ESTIMATING FOR A 100,000 GPD PRESSURE ION-EXCHANGE SYSTEM

STEP 1 - CALCULATE COST ADJUSTMENT FACTORS AS OF JUNE 1982

A. Construction Cost Escalation Factor (CCEF) $= \frac{\text{Current ENR CCI}}{\text{Base ENR CCI}}$

The cost curves of Reference 1 are based on October 1978 costs, when the ENR Construction Cost Index (CCI) was 265.38. The June 1982 ENR CCI was 352.92.

Therefore, CCEF $= \frac{352.92}{265.38} = 1.33$

B. Maintenance Material Cost Escalation Factor (MMCEF) $= \frac{\text{Current PPI}}{\text{Base Year PPI}}$

The October 1978 Producers Price Index (PPI) issued by the U. S. Department of Commerce, was 199.7. The June 1982 PPI was 299.4.

Therefore, MCEF $= \frac{299.4}{199.7} = 1.50$

STEP 2 - ESTIMATE CONSTRUCTION COST USING FIGURE 6-6

From Figure 6-6, construction cost in October 1978 dollars is $70,000.

June 1982 = 70,000 x CCEF
Contruction Cost = 70,000 x 1.33
= $93,100

STEP 3 - SPECIAL COSTS

Assume that special site work for foundation pilings costs $9,000, and that standby power requirements cost $10,000. Assume that no costs are associated with spent brine disposal.

STEP 4 - TOTAL CONSTRUCTION COST

Construction Cost:	$ 93,100
Special Cost:	19,000
Total Construction Cost	$112,100

STEP 5 - CALCULATE CAPITAL COST

From Figure 6-1, general contractor's overhead and profit for a total construction cost of $112,100 is found to be 12 percent of total construction cost.

Assume that engineering fees are 10 percent of total construction cost and general contractor's overhead and profit, and that land costs are $30,000. Calculate the sum of total construction, general contractor overhead and profit, engineering and land costs.

Total Construction	$112,100
General Contractor Overhead and Profit, 0.12 (112,100)	13,500
Subtotal	125,600
Engineering at 10%, 0.10 (125,600)	12,600
Subtotal	138,200
Land	30,000
SUBTOTAL	$168,200

From Figure 6-2, legal fiscal and administrative costs are found to be $5,000. Assume that interest paid on the construction loan will be 10 percent per annum. From Figure 6-4, interest during construction is $4,000. Calculate total capital cost:

Subtotal of Other Costs	$168,200
Legal, Fiscal, and Administrative Costs	5,000
Interest during Construction	4,000
TOTAL CAPITAL COST	$177,200

STEP 6 - ESTIMATE ANNUAL OPERATING AND MAINTENANCE COST

A. Energy Cost

Energy Use - Process Energy + Building Energy*

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* Building energy is very dependent on climate. If possible, estimate directly for your area.

B. Maintenance Material

From Figure 6-7, October 1978, annual maintenance material cost is $850.

June 1982 = $850 x MMCEF
Maintenance Material = $850 x 1.50
Cost = $1,300

From Figure 6-7,

Energy Use = 14,200 kwh/yr +
2,000 kwh/year
= 16,200 kwh/year

$$\text{Energy Cost/year} = \text{kwh/year} \times \frac{\text{energy cost}}{\text{kwh}}$$

For this example, assume energy cost of $0.05/kwh

Energy cost/year = 16,200 x $0.05
= $810

C. Labor Cost

From Figure 6-8, labor = 1,200 hr/yr for a 100,000 gpd system. If labor costs $12.00/hr (including fringe costs), annual labor cost is calculated as follows:

Annual labor cost = 1,100 hr/yr x $12.00/hr
= $14,400

D. Regenerant (Salt) Cost

Assume that the ion-exchange resin manufacturer has calculated that:

250 lbs of salt per 100,000 gal treated water are required for regeneration, and that salt costs $0.03/lb.

$$\text{Cost per day} = 100{,}000 \text{ gal/day} \times \frac{250 \text{ lbs salt}}{100{,}000 \text{ gal}} \times \frac{\$0.03}{\text{lb salt}}$$

$$= \$7.50/\text{day}$$

$$\text{Cost per year} = 365 \text{ days/yr} \times \frac{\$7.50}{\text{d}} = \$2{,}800/\text{year}$$

E. Total Annual O&M Cost

Energy	$ 800
Maintenance Material	1,300
Labor	14,400
Salt	2,800
Total Annual O&M Cost	$19,300

STEP 7 - ANNUALIZE CAPITAL COST

If the cost of money is 10 percent, and the system has a 20-year design life, the annualized capital cost is computed as follows:

Annualized Capital Cost = Capital Cost x Capital Recovery Factor at interest rate of 10 % for 20 years

The capital recovery factor from Table I for 10 percent and 20 years is 0.117460

Annualized Capital Cost = $177,200 x 0.007460
= $20,820

STEP 8 - CALCULATE TOTAL ANNUAL COST AND COST PER 1,000 GALLONS TREATED

A. Annual Cost Calculation

Annualized Capital Cost	= $20,820
Total Annual O&M Cost	= $19,300
Total Annual Cost	= $40,120

B. Annual Treated Flow, Thousands of Gallons

$$\text{Annual Treated Flow (1,000 gal)} = \frac{100{,}000\text{ gal}}{\text{day}} \times \frac{1}{1{,}000} \times 365$$

$$= 36{,}500 \text{ thousand gallons}$$

C. Cost per 1,000 Gallons Treated

$$\text{Cost/1,000 gal} = \frac{\text{Annual Cost}}{\text{Annual Treated Flow (1,000 gal)}}$$

$$= \frac{\$40{,}120}{36{,}500 \text{ thousand gallons}}$$

$$\text{Cost/1,000 gal} = \$1.10$$

FUNDING SOURCES

The principal financing options to small water systems for treatment process improvement for radionuclide removal can be categorized as follows:

- Self-Financing
  - User charges and fees
  - Bonding/loans
- Direct Grant Programs
- Subsidized/Assisted Loan Programs
- Other Assistance Programs
  - Labor sharing with other systems
  - EPA technical assistance activities

These are discussed in turn as follow.

Self-Financing

Water utilities process, deliver and charge consumers for potable water. In this, they bear close resemblance to other businesses that also produce and sell a product. Most of these utilities, publicly or privately owned, do not normally have problems in financing needed capital improvements either through user fees or changes in the water rate, or by bonding. However, the financing needs for constructing and operating radionuclide removal systems may severely strain small community water systems, either by requiring capital expenditures beyond their ability to finance, or by causing very large incremental increases in user charges. The latter course may incur substantial consumer resistance to the improvement program, a major impediment in the case of publicly owned systems. Very small systems may be particularly vulnerable to problems in this regard--one study indicates that up to 30 percent of systems serving less than 500 people may be unable to finance radionuclide removal unassisted.

The prime considerations for self-financing include the following:

- o Amount of revenues available for payment of interest costs
- o Ratio of new treatment capital costs to existing assets
- o Percent rate increase needed to finance and operate treatment
- o Ratio of the typical residential water bill to the community's median family income

In competing for funds on the private capital markets, the larger utility is expected to have a debt service ratio (ratio of income after operating expense to interest costs) of 1.3 and income at least twice that of interest charges. Private utilities must be showing a net profit, after taxes, of 10 to 13 percent. User bills should run less than 1.5 to 2.0 percent of median family income.

Smaller utilities may be substantially less robust financially, and still be able to raise money locally. Utility customers may be willing and able to put up the needed capital. Even so, the utility should have a debt service ratio of at least 1.0 so interest and bond repayment schedules can be met.

Grant Programs

The principal financial assistance program available to small community water system (public or private nonprofit) is operated by the Farmers Home Administration (FmHA) of the Department of Agriculture. FmHA can grant up to 75 percent of the cost for installation, repair or upgrading community water systems that serve fewer than 10,000 people with emphasis on farmers and other rural residents.

Program aid priorities are as follows:

- o Public bodies and towns with emphasis to those serving 5,500 people or less
- o Assist compliance with Safe Drinking Water Act
- o Low income communities
- o Systems proposing to merge and/or regionalize
- o State recommended projects
- o Projects promoting water energy conservation

Principal grant award criteria are:

1. User charges must be at least equal to other similar, already established systems, on the basis of:
    - o Similar costs of construction and operation
    - o Similar economic conditions
2. Debt service costs exceed net levels as determined by the ratio of mean family cost for water service to median family income. Specifically:
    - o For communities of median family income less than $6,000 debt

service must exceed 0.75 percent of median family income to be eligible.

- For communities of median family income $6,000 to $10,000, debt service/income must exceed 1.0 percent for eligibility.
- For communities exceeding $10,000 median family income, debt service/income must exceed 1.25 percent for eligibility.

FmHA can be contacted for further information at any one of 340 offices nationwide.

The Economic Development Administration (EDA) has some limited programs for water/sewer assistance, primarily keyed to promoting industrial development and creating jobs. Grants can range from 50 to 80 percent of project costs (up to 100 percent for Indian Tribes) and public or private nonprofit agencies may qualify. EDA has six regional offices and staff in each of the 50 states.

Direct Loan Programs

Three federal agencies operate direct loan programs:

- Department of Interior - has two programs available to public nonfederal entities in the 17 western states.
- Farmers Home Administration - has loan program with similar criteria to those used in their grant program. The loan can be for 100 percent of the project cost.
- Small Business Administration - has a number of loan programs that may be used by small investor-owned water utilities. Loans cannot exceed $150,000.

Loan Guarantee Programs

Both the Small Business Administration (SBA) and the Farmers Home Administration (FmHA) can provide backing for privately placed loans as follows:

- SBA - will guarantee up to 90 percent of a loan up to $500,000 for private, independent businesses that are refused a bank loan.
- FmHA - has a Business and Industry Loan Program available to public or private organizations, particularly those located in rural areas and serving fewer than 2,500 persons. Loan guarantees range up to 90 percent of face value.

Other Forms of Assistance

Other ways of reducing financing and/or operating costs include the following:

- Bond banks - Several states have central bond banks that assist localities in the mechanics of bond financing. By aggregating small bonds into larger ones, interest costs may be reduced and bond placement enhanced.
- Research and development - The U.S. Environmental Protection Agency (EPA) has funded pilot and demonstra-

tion projects for water and wastewater systems using uncommon technology.

- State loan programs - Several states provide direct loans for contruction of public water and sewer projects. The programs are normally operated under the aegis of state economic development offices.

- Shared operator costs with other nearby utility(s) - Ion exchange radionuclide removal does not require full time supervision; hence, operator costs could be divided up between two or more utilities where travel distance permits. (Regionalization is one approach to shared operating expenses.

VII. OPERATION AND MAINTENANCE

An operator is defined as any person, including the owner, who is in actual charge of the operation, supervision, or maintenance of a water purification plant. Most water plant operators will not have the training required for radionuclide removal, particularly for the treatment processes of lime softening, reverse osmosis, or ion exchange. Therefore, on-the-job training will be necessary and will rely on extensive help from the equipment manufacturer and/or the design engineer.

On-the-job training complemented by formal training programs are best for the processes described above. Information on short courses and seminars is available from the state certification and training office or the Board of Health or equivalent agency in any given state. Organizations such as the American Water Works Association and the Rural Water Association also conduct training programs and can provide information about local programs.

The operator should be reasonably proficient in plumbing and electrical skills and have an understanding of the operation and repair of simple pumps, valves, water meters and electrical controls fundamental to successful operation and maintenance. He or she must be capable of carrying out a program of periodic sampling and be able to use a packaged test kit for alkalinity and hardness as well as be able to use a pH meter and conduct total dissolved solids tests. The operator will need to be knowledgeable of sampling techniques for radionuclides but will not likely be required to be able to analyze for them. A working knowledge of fundamental chemistry will be essential. The operator will be required to make simple calculations and record results.

The operator should also be of sufficient intelligence and schooling so that he or she can be trained in the fundamentals of process operation and be able to fully grasp the importance of avoiding excessive radionuclide concentrations in the finished water.

Operator time requirements are dependent on system size and may be regulated by the states. In general 2 to 3 hours per day will be necessary in order to ensure everything is working properly and to carry out sampling (monitoring) and maintenance procedures.

MANPOWER REQUIREMENTS

For plants processing less than 0.5 MGD, it is generally recommended that one certified operator be in charge of the operation of a lime-soda softening plant, reverse osmosis, or ion-exchange system. While no federal requirements exist for operator certification, state requirements do. These requirements vary from state to state, however, so the state regulatory agency should be consulted.

To assist the operator in sampling, lubricating, cleaning, maintenance, and general housekeeping, a

Maintenance Helper or semi-skilled laborer may also be required. This position may be part-time depending on the design flow, actual equipment installed, and local conditions.

MANAGEMENT AND RECORD KEEPING

The operator's management responsibility generally includes running the facility within acceptable state and local guidelines and within an approved operating budget. Specific responsibilities are listed in the Appendix.

Only through concise and accurate reporting of occurrences and accomplishments will past experience be helpful in handling future operational situations. Complete records are necessary for interpreting the results of the treatment process. In the event of legal questions pertaining to water quality, records are required as evidence of what occurred at any given time or over a certain time period. Various local, state, and federal regulatory agencies also receive water quality reports.

Records also provide an excellent checklist on current and future work, especially maintenance tasks. Well-kept records should note when service was last performed on each piece of major equipment and when future service will be required.

Financial records are necessary to enable an accurate budget to be prepared for the plant. Financial records also will indicate possible process or operational changes whereby the cost of efficiently handling various unit processes may be reduced.

The following records are considered necessary for efficient operations:

1. Daily operating logs,
2. Monthly operating report,
3. Reports to state agencies,
4. Reports to federal agencies,
5. Annual report, and
6. Maintenance records.

Daily operating logs usually include: (1) public complaints, (2) facility visitors, (3) personnel injuries, (4) alarm status reports, (5) routine operational duties, and (6) unusual operation and maintenance conditions.

The equipment manufacturer will normally illustrate the specific maintenance records to be kept. The following records, as a minimum, should be readily available at the plant:

1. As-built engineering drawings,
2. Copy of construction specifications,
3. Equipment supplier's operation and maintenance manuals,
4. Piping and wiring diagrams,
5. Construction photographs (if available),
6. Lubrication records, and
7. Major repair history.

These records should be periodically reviewed and updated when warranted.

Lists of purchases and expenses during the fiscal year should be kept up to date and comparisons should be made with budget allocations to avoid excess expeditures.

The major categories of financial expenditures are labor, utilities, chemicals, and facility supplies, and can be broken down as follows:

Labor	Utilities	Chemicals	Facility Supplies
Operations	Electricity	Chlorine	Laboratory chemicals
Administration	Fuel	Lime, soda-ash	Cleaning materials
Maintenance	Telephone	Caustic soda	Maintenance supplies
	Potable Water	Sulfuric acid	Spare parts
		Polymers	Other expendable items
		Other necessary chemicals for treatment process	

A systematic filing arrangement of all records to eliminate the possibility of loss and deterioration and to permit ready access and prompt location of specific data is an essential part of a complete laboratory records system.

To enable record keeping to be neat and legible, forms should also be provided and used. A ball-point pen or a pencil hard enough to resist smudging should be used in recording data on the various forms. Neat, legible data will greatly reduce the number of errors in data compilation and subsequent use.

EMERGENCY PROCEDURES

Emergency conditions generally result from either natural or manmade causes. The primary concern during a natural disaster should be the safety of plant personnel and the integrity of the water quality. Temporary failure to remove radionuclides will be of secondary importance at times when there is no water being produced by the plant or when there is a lack of disinfection capability. Therefore, the plant operator's actions in a recovery phase will be: first, to restore water pressure, and secondly to restore the disinfection.

Specific emergency equipment procedures are available from the manufacturers. By reviewing these procedures periodically, the operator will be ready to respond as needed. Examples would include emergency power generation or auxiliary direct-drive engines, adequate water supply and pressure to the chlorinators and extra sampling of the system for bacteriological monitoring.

SAFETY PROCEDURES

Without adequate safety precautions, the operation of any water plant is a dangerous occupation.

Radionuclide removal systems may use moving mechanical equipment, electrical motors and switchgear, caustic and acidic chemicals, and chlorination equipment, all of which require a basic understanding of safe practices.

Good housekeeping is an important factor in plant safety. All equipment and structures should be kept orderly and in good repair. Walkways should be guarded with handrails and free from oil and grease. By careful use of equipment only as it is intended to be used, accidents can be minimized. Special precaution should be taken near electrical and mechanical equipment. Examples follow:

1. The manufacturers' instructions regarding the proper operation and maintenance procedures for each piece of mechanical equipment in the facility should be followed. When working on a piece of mechanical equipment, all power to the equipment should be shut off by opening the proper control switch locking it out, and tagging it to prevent others from closing it. Never attempt to perform preventive or corrective maintenance on machinery that is operating, unless directed otherwise in the manufacturers' instruction manual and verified by your own evaluation of the site-specific conditions.

2. Do not perform work on a piece of electrical equipment while standing on a wet or damp floor. A rubber mat should be placed on the floor in front of electrical panels as an added precaution. Do not use metal ladders around electrical equipment, and only use properly grounded electrical tools.

3. Post emergency telephone numbers at each plant telephone. Also post numbers for chemical equipment suppliers and manufacturers. In case of emergency, contact the owner, and state regulatory agency.

MAINTENANCE PROCEDURES

The specific maintenance functions will be described by the equipment manufacturers and will include duties not required of every operator because specific equipment may require certain skills or tools.

General maintenance for the three types of systems proposed for radionuclide removal are given below:

1. Maintenance for Reverse Osmosis (RO) Systems
2. Maintenance for Ion Exchange Systems
3. Maintenance for Lime (Soda) Softening Systems

Maintenance for Reverse Osmosis Systems

Since the RO membrane literally filters water, the membrane is sensitive to clogging with particulate material, iron, manganese, turbidity, organic substances and certain other undissolved impurities in the water. Therefore, considerable attention has to be given to the pretreatment requirements for RO membranes in the design and selection of equipment.

Nevertheless, there will still be the need to periodically clean the membranes.

The method used for cleaning will depend on the type of membrane used and specific manufacturer's suggestions, however, the most common techniques used are foam ball swabbing and flushing with chemical additives at low pressure.

The cleaning schedule or frequency will vary from system to system depending on the nature of the water being treated. The symptoms of operation that dictate cleaning the membranes are any one of the following:

- excessive pressure drop across the membrane (20-50 psi above the original pressure drop of start-up)
- excessive decline of permeate flow
- increasing total dissolved solids in product water or excessive radionuclide passage.

Other maintenance associated with RO systems would involve the following items of major equipment:

1. high pressure pump (400-600 psi)
2. high pressure valves and seals
3. chemical feed pumps
4. chemical feed make-up and storage
5. reject water disposal systems
6. normal maintenance associated with storage tanks, system service pumps, and chlorinators.

Maintenance for Ion Exchange Systems

Typical preventive maintenance checks:

- o Pumps (if any):
  - Overheating. The pump motor should not burn the hand when touched or smell hot.
  - Noisiness/vibration. Rattling and grinding noises may indicate serious bearing problems and/or shaft misalignment.
  - Water leaks from packing glands and fittings.
  - Loose hardware, mountings, electrical connections.
  - Surface rusting/corrosion.
  - Motor ventilation ports. Ports should be clear and free of dirt, oil and moisture.
- o Motorized flow valves:
  - Water, oil leaks.
  - Rough operation, noisiness during regeneration cycle.
  - Leaks from waste line when valve is in the "off" or "in service" position.
  - Proper valve positioning.
- o Flow meters/flow totalizers:
  - Comparison of main flow meter and check flow meter for equivalent recordings.
  - Leaking, moisture under meter glass, sticking of meter in operation.
- o Blending flow valve/flow meters:
  - Check daily for correct flow splitting.

- Brine/salt storage:
  - Salt level in brine tank.
  - Stored salt quantity.
- Tanks, pipes and appurtenances:
  - Leaks, cracks, corrosion.

Checks During Regeneration

- Check time clock and relays for:
  - Noisiness
  - Sticking
  - Overheating or hot smell
  - Time accuracy
- Check automatic valve for:
  - Leaking
  - Sticking
  - Complete cycling
- Check brine system for:
  - Flow meter operation
  - Adequate salt in brine tanks
- Waste flow:
  - Free flowing
  - Evidence of resin in waste flow

Other Periodic Acitivities

- Pumps/motors:
  - Lubricate per manufacturer's recommendation
- Flow meters:
  - Calibrate per manufacturer's recommendation
- Time clock/relays/automatic valve:
  - Lubricate, adjust per manufacturer's recommendation

Maintenance for Lime-Soda Softening Systems

Maintenance of this equipment involves at least twice yearly draining the clarifier structure for cleaning and to remove scale. The turbine or mixer sludge rake arms (if applicable) should also be checked for clearance and operation.

The chemical feed systems - such as lime slurry will need daily inspection to remove sediments that may settle out and clog the piping. The chemical feed pumps should be calibrated at least once a week to ensure reliability of feeds. Caution must be used when working with the lime slurry feed system since the solutions are caustic and will cause skin burns.

Filters associated with these plants will have to be maintained by proper backwashing and cleaning in order to prevent mud-ball formation in the media and to ensure good consistent turbidity removals. Normally filters are washed on a head loss or effluent turbidity monitoring basis dependent on type. Typical filter hours for softening plants are 40 to 150 hours between backwashes. Any electrical or hydropneumatic controls associated with these units should be calibrated and maintained at least quarterly.

VIII. CASE HISTORIES

This section presents a case history for each method of radionuclide removal described earlier, including:

1. Lime-soda softening,
2. Ion exchange and blending of treated and untreated water, and
3. Reverse osmosis.

LIME-SODA SOFTENING

The water treatment plant in Peru, Illinois, is an example of a small plant which treats a raw water having an Ra-226 concentration which exceeds the MCL of 5 pCi/l. The raw water is pumped from three wells. Treatment consists of aeration, addition of lime and soda ash, clarification, sedimentation, chlorination, and filtration. Full treatment is provided to 60 percent of the raw water which is then blended with 40 percent, which is filtered but not softened. An average of 1.8 MGD is processed by the treatment plant and pumped to the distribution system. Treatment system design criteria and operating data are presented below:

Aerator
Type: Coke tray with forced draft
Area: 324 ft^2
Capacity: 1,620 gpm

Lime and Soda Ash Addition
Average amount of lime added: 1.87 lb/1,000 gal
Average volume of soda ash added: 0.008 gal/1,000 gal

Clarifier

Dimensions: 30-ft diameter, 14-ft depth
Volume: 74,000 gal
Weir Loading Rate: 14 gpm/ft

Settling Tank

Dimensions: 36 ft x 30 ft x 14.5 ft (Tank 1)
16 ft x 20 ft x 14.5 ft (Tank 2)
Total Volume: 152,000 gal

Recarbonator

Dimensions: 14.5 ft x 5 ft x 12 ft
Volume: 6,510 gal

Gas Chlorinator

Capacity: 50 lb/day
Source: 150 lb cylinder

Filters

Number of Units: Three
Type: Gravity rapid sand
Filter Area: 170 ft^2
Capacity: 2 gpm/ft^2

Table 8-1 presents reduction data for Ra-226 and hardness for 3 days of sampling. These data show the radium removal is above 70 percent with an effluent radium concentration below 2 pCi/l.

The chemical cost (lime and soda ash) for this plant is approximately $75 per day, which is $0.04 per 1,000 gallons based on the treated flow of 1.8 MGD. The construction cost for this plant,

TABLE 8-1

REDUCTION OF Ra-266 AND HARDNESS, PERU, ILLINOIS BEFORE BLENDING

Sampling Date	Raw Water Concentration		Softened Water Concentration		Percent Reduction	
	Ra-226 (pCi/1)	Hardness (mg/1 as $CaCO_3$)	Ra-226 (pCi/1)	Hardness (mg/1 as $CaCO_3$)	Ra-226	Hardness
2/19/75	6.39	329	0.48	70	92.4	78.7
2/25/75	5.49	320	1.61	100	70.6	68.8
3/04/75	5.48	329	1.21	112	77.9	66.0

Source: EPA, 1976.

as well as other operating costs, are not available.

ION EXCHANGE AND BLENDING OF TREATED AND UNTREATED WATER

The village of Lynwood, Illinois, has an ion-exchange water treatment plant which treats an average of 158,000 gpd. This plant removes hardness and Ra-226 from the raw water which is pumped from a deep well. Treatment consists of ion exchange, using a styrene-based zeolite resin, and chlorination. Approximately 90 percent of the raw water receives ion-exchange treatment and is blended with 10 percent of the raw water prior to chlorination. Design criteria for this treatment system are presented in the following lists:

Ion-Exchange Units

Number of Units: Three
Dimensions: 90-in diameter, 7.5-ft height
Resin Volume in Each Unit: 206 ft^3
Bed Depth: 53 in
Resin Capacity: 11 $kgrCaCO_3/ft^3$
Total Capacity (per units): 2,266 kgr

Gas Chlorinator Capacity: 100 lb/day

Source: 150-lb cylinder

Table 8-2 presents Ra-226 reduction data for 3 days of sampling. Radium removal is shown to be above 97 percent producing a softened water with a radium concentration of less than 0.5 pCi/l.

TABLE 8-2

Ra-266 REDUCTION, LYNWOOD, ILLINOIS

Sampling Date	Ra-226 Concentration* (pCi/l)		Percent Reduction
	Raw	Softened+	
3/27/75	14.80	0.26	98.2
4/02/75	14.70	0.36	97.6
4/10/75	14.90	0.27	98.2

* Samples collected midway between regeneration of resin.
+ Following ion-exchange treatment.

Source: EPA, ORP/TAD-76-2.

The construction cost of this ion-exchange treatment plant, as built in 1972, was $150,000. The operating cost is approximately $1,520 per month, which is $0.32 per 1,000 gallons of treated water based on a flow of 158,000 gpd. The operating cost does not include amortization of the construction cost.

REVERSE OSMOSIS

The reverse osmosis treatment plant which provides potable water for the Sarasota Bay Mobile Home Park in Sarasota County, Florida, is a good example of a small plant treating a raw water with a high Ra-226 content. Raw water is pumped from a well and pretreated by the addition of hydrochloric acid for pH adjustment and sodium hexametaphosphate as a sequestering agent. The pretreated water is then pumped through the reverse osmosis units, which are equipped with hollow-fiber membranes, at an operating pressure of 400 psi. Posttreatment consists of aeration, after which the water is chlorinated. No blending is conducted at this plant. The average flow through the plant is 5,000 gpd.

The average hardness and Ra-226 concentrations in the raw water are approximately 1,612 mg/l (as $CaCO_3$) and 20.5 pCi/l, respectively. The treated water concentrations of hardness and Ra-226 are approximately 34 mg/l (as $CaCO_3$) and 0.32 pCi/l, respectively. This represents a 97.9-percent removal for hardness and a 98.4-percent removal for Ra-226. These data are based on sampling conducted from March through April 1977.

The construction cost of this reverse osmosis treatment plant, built in 1975, was $70,000. The estimated operating cost is $1.22 per 1,000 gallons of treated water, based on a flow of 5,000 gpd. The operating cost does not include amortization and membrane replacement.

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APPENDIX A

CHEMICAL ELEMENT SYMBOLS
AND
ATOMIC NUMBERS

Chemical element symbols and atomic numbers

Chemical Element	Symbol	Atomic Number
Actinium	Ac	89
Aluminum	Al	13
Americium	Am	95
Antimony	Sb	51
Argon	Ar	18
Arsenic	As	33
Astatine	At	85
Barium	Ba	56
Berkelium	Bk	97
Beryllium	Be	4
Bismuth	Bi	83
Boron	B	5
Bromine	Br	35
Cadmium	Cd	48
Calcium	Ca	20
Californium	Cf	98
Carbon	C	6
Cerium	Ce	58
Cesium	Cs	55
Chlorine	Cl	17
Chromium	Cr	24
Cobalt	Co	27
Copper	Cu	29
Curium	Cm	96
Dysprosium	Dy	66
Einsteinium	Es	99
Erbium	Er	68
Europium	Eu	63
Fermium	Fm	100
Fluorine	F	9
Francium	Fr	87
Gadolinium	Gd	64
Gallium	Ga	31
Germanium	Ge	32
Gold	Au	79
Hafnium	Hf	72
Helium	He	2
Holmium	Ho	67
Hydrogen	H	1
Indium	In	49
Iodine	I	53
Iridium	Ir	77
Iron	Fe	26
Krypton	Kr	36
Lanthanium	La	57
Lawrencium	Lr	103
Lead	Pb	82
Lithium	Li	3
Lutetium	Lu	71
Magnesium	Mg	12
Manganese	Mn	25
Mendelevium	Md	101

Chemical Element	Symbol	Atomic Number
Mercury	Hg	80
Molybdenum	Mo	42
Neodymium	Nd	60
Neon	Ne	10
Neptunium	Np	93
Nickel	Ni	28
Niobium	Nb	41
Nitrogen	N	7
Nobelium	No	102
Osmium	Os	76
Oxygen	O	8
Palladium	Pd	46
Phosphorus	P	15
Platinum	Pt	78
Plutonium	Pu	94
Polonium	Po	84
Potassium	K	19
Praseodymium	Pr	59
Promethium	Pm	61
Protactinium	Pa	91
Radium	Ra	88
Radon	Rn	86
Rhenium	Re	75
Rhodium	Rh	45
Rubidium	Rb	37
Rutheium	Ru	44
Samarium	Sm	62
Scandium	Sc	21
Selenium	Se	34
Silicon	Si	14
Silver	Ag	47
Sodium	Na	11
Strontium	Sr	38
Sulfur	S	16
Tantalum	Ta	73
Technetium	Tc	43
Tellurium	Te	52
Terbium	Tb	65
Thallium	Tl	81
Thorium	Th	90
Thulium	Tm	69
Tin	Sn	50
Titanium	Ti	22
Tungsten	W	74
Uranium	U	92
Vanadium	V	23
Xenon	Xe	54
Ytterbium	Yb	70
Yttrium	Y	39
Zinc	Zn	30
Zirconium	Zr	40

APPENDIX B

AVERAGE ANNUAL CONCENTRATIONS
YIELDING 4 MILLIREM PER YEAR

Annual Average Concentrations Yielding 4 Millirem per Year for a Two Liter Daily Intake, From National Interim Primary Drinking Water Regulations, EPA-570/9-76-003

Half-Life Greater than 24 Hours

Radionuclide	Critical Organ	C4 (pCi/l)
Tritium	Total Body	20,000
${}^{7}_{4}Be$	GI (LLI)	6,000
${}^{14}_{6}C$	Fat	2,000
${}^{22}_{11}Na$	Total Body	400
${}^{24}_{11}Na$	GI (S)	600
${}^{32}_{15}P$	Bone	30
${}^{35}_{16}S$	Testis	500
${}^{36}_{17}Cl$	Total Body	700
${}^{45}_{20}Ca$	Bone	10
${}^{47}_{20}Ca$	Bone	80
${}^{46}_{21}Sc$	GI(LLI)	1,000
${}^{47}_{21}Sc$	GI(LLI)	300
${}^{48}_{21}Sc$	GI(LLI)	80
${}^{48}_{23}V$	GI(LLI)	90
${}^{51}_{24}Cr$	GI(LLI)	6,000

Radionuclide	Critical Organ	C4 (pCi/l)
${}^{52}_{25}Mn$	GI(LLI)	90
${}^{54}_{25}Mn$	GI(LLI)	300
${}^{55}_{26}Fe$	Spleen	2,200
${}^{59}_{26}Fe$	Gl(LL1)	200
${}^{57}_{27}Co$	GI(LLI)	1,000
${}^{58}_{27}Co$	GI(LLI)	300
${}^{60}_{27}Co$	GI(LLI)	100
${}^{59}_{28}Ni$	Bone	300
${}^{63}_{28}Ni$	Bone	50
${}^{65}_{30}Zn$	Liver	300
${}^{71}_{32}Ge$	GI(LLI)	6,000
${}^{73}_{33}As$	GI(LLI)	1,000
${}^{74}_{33}As$	GI(LLI)	100
${}^{76}_{33}As$	GI(LLI)	60
${}^{77}_{33}As$	GI(LLI)	200
${}^{75}_{34}Se$	Kidney	900

Radionuclide	Critical Organ	C4 (pCi/l)
${}^{82}_{35}\mathrm{Br}$	GI(LLI)	100
${}^{86}_{37}\mathrm{Rb}$	Total Body	600
${}^{87}_{37}\mathrm{Rb}$	Pancreas	300
${}^{85}_{38}\mathrm{Sr}$	GI(SI)	21,000
${}^{89}_{38}\mathrm{Sr}$	Bone	20
${}^{89}_{38}\mathrm{Sr}$	Bone Marrow (FRC)	80
${}^{90}_{38}\mathrm{Sr}$	Bone Marrow (FRC)	8
${}^{90}_{39}\mathrm{Y}$	GI(LLI)	60
${}^{91}_{39}\mathrm{Y}$	GI(LLI)	90
${}^{93}_{40}\mathrm{Zr}$	GI(LLI)	2,000
${}^{95}_{40}\mathrm{Zr}$	GI(LLI)	200
${}^{93m}_{41}\mathrm{NB}$	GI(LLI)	1,000
${}^{95}_{41}\mathrm{NB}$	GI(LLI)	300
${}^{99}_{42}\mathrm{Mo}$	Kidney	600
${}^{96}_{43}\mathrm{Tc}$	GI(LLI)	300
${}^{97m}_{43}\mathrm{Tc}$	GI(LLI)	1,000

Radionuclide	Critical Organ	C4 (pCi/1)
${}^{97}_{43}\text{Tc}$	GI(LLI)	6,000
${}^{99}_{43}\text{T}$	GI(LLI)	900
${}^{97}_{44}\text{Ru}$	GI(LLI)	1,000
${}^{103}_{44}\text{Ru}$	GI(LLI)	200
${}^{106}_{44}\text{Ru}$	GI(LLI)	30
${}^{105}_{45}\text{Ru}$	GI(LLI)	300
${}^{103}_{46}\text{Pd}$	GI(LLI)	900
${}^{109}_{46}\text{Pd}$	GI(LLI)	300
${}^{105}_{47}\text{Ag}$	GI(LLI)	300
${}^{110m}_{47}\text{Ag}$	GI(LLI)	90
${}^{111}_{47}\text{Ag}$	GI(LLI)	100
${}^{109}_{48}\text{Cd}$	GI(LLI)	600
${}^{115m}_{48}\text{Cd}$	GI(LLI)	90
${}^{115}_{48}\text{Cd}$	GI(LLI)	90
${}^{115}_{49}\text{In}$	GI(LLI)	300
${}^{113}_{50}\text{Sn}$	GI(LLI)	300

Radionuclide	Critical Organ	C4 (pCi/l)
$^{125}_{50}\mathrm{Sn}$	GI(LLI)	60
$^{122}_{51}\mathrm{Sb}$	GI(LLI)	90
$^{124}_{51}\mathrm{Sb}$	GI(LLI)	60
$^{125}_{51}\mathrm{Sb}$	GI(LLI)	300
$^{125m}_{52}\mathrm{Te}$	Kidney	600
$^{127m}_{52}\mathrm{Te}$	Kidney	200
$^{127}_{52}\mathrm{Te}$	GI(LLI)	900
$^{129m}_{52}\mathrm{Te}$	GI(LLI)	90
$^{129}_{52}\mathrm{Te}$	GI(S)	2,000
$^{131m}_{52}\mathrm{Te}$	GI(LLI)	200
$^{132}_{52}\mathrm{Te}$	GI(LLI)	90
$^{125}_{53}\mathrm{I}$	Thyroid	3
$^{126}_{53}\mathrm{I}$	Thyroid	3
$^{129}_{53}\mathrm{I}$	Thyroid	1
$^{131}_{53}\mathrm{I}$	Thyroid	3
$^{131}_{55}\mathrm{Cs}$	Total Body	20,000

Radionuclide	Critical Organ	C4 (pCi/l)
$^{134}_{55}\mathrm{Cs}$	Total Body	80
$^{135}_{55}\mathrm{Cs}$	Total Body	900
$^{136}_{55}\mathrm{Cs}$	Total Body	800
$^{137}_{55}\mathrm{Cs}$	Total Body	200
$^{131}_{56}\mathrm{Ba}$	GI(LLI)	600
$^{140}_{56}\mathrm{Ba}$	GI(LLI)	90
$^{140}_{57}\mathrm{La}$	GI(LLI)	60
$^{141}_{58}\mathrm{Ce}$	GI(LLI)	300
$^{143}_{58}\mathrm{Ce}$	GI(LLI)	100
$^{143}_{58}\mathrm{Pr}$	GI(LLI)	100
$^{149}_{61}\mathrm{Pm}$	GI(LLI)	100
$^{151}_{62}\mathrm{Sm}$	GI(LLI)	1,000
$^{153}_{62}\mathrm{Sm}$	GI(LLI)	200
$^{152}_{63}\mathrm{Eu}$	GI(LLI)	60
$^{154}_{63}\mathrm{Eu}$	GI(LLI)	200
$^{153}_{64}\mathrm{Gd}$	GI(LLI)	600

Radionuclide	Critical Organ	C4 (pCi/l)
${}^{160}_{65}\mathrm{Tb}$	GI(LLI)	600
${}^{166}_{66}\mathrm{Dy}$	GI(LLI)	100
${}^{166}_{67}\mathrm{Ho}$	GI(LLI)	100
${}^{169}_{68}\mathrm{Er}$	GI(LLI)	90
${}^{170}_{68}\mathrm{Tm}$	GI(LLI)	300
${}^{170}_{69}\mathrm{Tm}$	GI(LLI)	100
${}^{171}_{69}\mathrm{Tm}$	GI(LLI)	1,000
${}^{175}_{70}\mathrm{Yb}$	GI(LLI)	300
${}^{177}_{71}\mathrm{Lu}$	GI(LLI)	300
${}^{181}_{72}\mathrm{Hf}$	GI(LLI)	200
${}^{183}_{73}\mathrm{Ta}$	GI(LLI)	100
${}^{181}_{74}\mathrm{W}$	GI(LLI)	1,000
${}^{185}_{74}\mathrm{W}$	GI(LLI)	300
${}^{183}_{75}\mathrm{Re}$	GI(LLI)	2,000
${}^{186}_{75}\mathrm{Re}$	GI(LLI)	300
${}^{187}_{75}\mathrm{Re}$	GI(LLI)	9,000

Radionuclide	Critical Organ	C4 (pCi/1)
$^{185}_{76}Os$	GI(LLI)	200
$^{191}_{76}Os$	GI(LLI)	600
$^{193}_{76}Os$	GI(LLI)	200
$^{190}_{77}Ir$	GI(LLI)	600
$^{92}_{77}Ir$	GI(LLI)	100
$^{191}_{78}Pt$	GI(LLI)	300
$^{193m}_{78}Pt$	GI(LLI)	3,000
$^{193}_{78}Pt$	Kidney	3,000
$^{197}_{78}Pt$	GI(LLI)	300
$^{196}_{79}Au$	GI(LLI)	600
$^{198}_{79}Au$	GI(LLI)	100
$^{197}_{80}Hg$	Kidney	900
$^{203}_{80}Hg$	Kidney	60
$^{204}_{81}Tl$	GI(LLI)	300
$^{203}_{82}Pb$	GI(LLI)	1,000
$^{206}_{83}Bi$	GI(LLI)	100

Radionuclide	Critical Organ	C4 (pCi/1)
$^{207}_{83}Bi$	GI(LLI)	200
$^{233}_{91}Pa$	GI(LLI)	300

Half-Life Less than 24 Hours

Radionuclide	Critical Organ	C4 (pCi/1)
${}^{18}_{9}\mathrm{F}$	GI(SI)	2,000
${}^{31}_{14}\mathrm{Si}$	GI(S)	3,000
${}^{138}_{17}\mathrm{Cl}$	GI(S)	1,000
${}^{42}_{19}\mathrm{K}$	GI(S)	900
${}^{56}_{25}\mathrm{Mn}$	GI(LLI)	300
${}^{58m}_{27}\mathrm{Co}$	GI(LLI)	9,000
${}^{65}_{28}\mathrm{Ni}$	GI(LLI)	300
${}^{64}_{29}\mathrm{Cu}$	GI(LLI)	900
${}^{69m}_{30}\mathrm{Zn}$	GI(LLI)	200
${}^{69}_{30}\mathrm{Zn}$	GI(S)	6,000
${}^{72}_{31}\mathrm{Ga}$	GI(LLI)	100
${}^{85m}_{38}\mathrm{Sr}$	Total Body	900
${}^{91}_{38}\mathrm{Sr}$	GI(LLI)	200
${}^{92}_{38}\mathrm{Sr}$	GI(ULI)	200
${}^{91m}_{39}\mathrm{Y}$	GI(SI)	9,000
${}^{92}_{39}\mathrm{Y}$	GI(ULI)	200

Radionuclide	Critical Organ	C4 (pCi/l)
${}^{93}_{39}\mathrm{Y}$	GI(LLI)	90
${}^{97}_{40}\mathrm{Zr}$	GI(LLI)	60
${}^{97}_{41}\mathrm{Nb}$	GI(ULI)	3,000
${}^{96m}_{43}\mathrm{Tc}$	GI(LLI)	30,000
${}^{99m}_{43}\mathrm{Tc}$	GI(ULI)	20,000
${}^{105}_{44}\mathrm{Rh}$	GI(ULI)	300
${}^{103m}_{45}\mathrm{Rh}$	GI(S)	30,000
${}^{113m}_{49}\mathrm{In}$	GI(ULI)	3,000
${}^{114m}_{49}\mathrm{In}$	GI(LLI)	60
${}^{115m}_{49}\mathrm{In}$	GI(ULI)	1,000
${}^{132}_{53}\mathrm{I}$	Thyroid	90
${}^{133}_{53}\mathrm{I}$	Thyroid	10
${}^{134}_{53}\mathrm{I}$	Thyroid	100
${}^{135}_{53}\mathrm{I}$	Thyroid	30
${}^{134m}_{55}\mathrm{Cs}$	GI(S)	20,000
${}^{142}_{59}\mathrm{Pr}$	GI(LLI)	90

Radionuclide	Critical Organ	C4 (pCi/1)
$^{149}_{60}Nd$	GI(LLI)	900
$^{152}_{63}Eu$	GI(LLI)	200
$^{159}_{64}Gd$	GI(LLI)	200
$^{165}_{66}Dy$	GI(LLI)	1,000
$^{171}_{68}Er$	GI(ULI)	300
$^{187}_{74}W$	GI(LLI)	200
$^{188}_{75}Re$	GI(LLI)	200
$^{191m}_{76}Os$	GI(LLI)	9,000
$^{194}_{77}Ir$	GI(LLI)	90
$^{197m}_{78}Pt$	GI(ULI)	3,000
$^{202}_{81}Tl$	GI(LLI)	300

APPENDIX C

SAMPLING AND ANALYTICAL METHODS FOR RADIOACTIVITY

SAMPLING AND ANALYTICAL METHODS FOR RADIOACTIVITY SPECIFIED IN NIPDWR

(a) The methods specified in Interim Radiochemical Monitoring for Drinking Water, Environmental Monitoring and Support Laboratory, EPA-600/4-75-008, U.S. EPA, Cincinnati, Ohio 45268, or those listed below, are to be used to determine compliance with §§141.15 and 141.16 (radioactivity) except in cases where alternative methods have been approved in accordance with §141.27.

(1) Gross Alpha and Beta--Method 302 "Gross Alpha and Beta Radioactivity in Water", Standard Methods for the Examination of Water and Wastewater, 13th Edition, American Public Health Association, New York, New York, 1971.

(2) Total Radium--Method 304 "Radium in Water by Precipitation," Ibid.

(3) Radium-226--Method 305 "Radium-226 by Radon in Water," Ibid.

(4) Strontium-89, 90--Method 303 "Total Strontium and Strontium-90 in Water," Ibid.

(5) Tritium--Method 306 "Tritium in Water," Ibid.

(6) Cesium-134--ASTM D-2459 "Gamma Spectrometry in Water," 1975 Annual Book of ASTM Standards, Water and Atmospheric Analysis, Part 31, American Society for Testing and Materials, Philadelphia, Pennsylvania (1975).

(7) Uranium--ASTM D-2907 "Microquantities of Uranium in Water by Fluorometry," Ibid.

(b) When the identification and measurement of radionuclides other than those listed in paragraph (a) are required, the following references are to be used, except in cases where alternative methods have been approved in accordance with §141.27.

(1) Procedures for Radiochemical Analysis of Nuclear Reactor Aqueous Solutions, H.L. Krieger and S. Gold, EPA-R4-73-014. U.S. EPA, Cincinnati, Ohio, May 1973.

(2) HASL Procedure Manual, Edited by John H. Harley. HASL 300, ERDA Health and Safety Laboratory, New York, New York, 1973.

APPENDIX D

DISCUSSION OF RADIOACTIVE UNITS

DISCUSSION OF UNITS OF RADIOACTIVITY

The effect of radioactivity depends not only on the number of radiations emitted per second, but on the kind of radiations (alpha, beta, or gamma) and their energies. These properties are expressed in terms of the dose or "punch" given to tissue or matter.

As discussed in Section II, two units are used to define radioactive dosage. One unit of dose is called a rad (radiation absorbed); one rad is defined as the dose that deposits 100 ergs (a metric unit of energy) in one gram of matter (such as human tissue). Ten million ergs per second is one watt. In general, these units are quite large and engineering shorthand is used to simplify working with them. The following table gives the meaning of some useful and commonly used prefixes. As indicated in the Table D-1, a millimeter is one one-thousandth (1/1000) of a meter and a kilogram is a thousand grams. Similarly 1 picocurie (pCi) is one million millionth of a curie and is abbreviated 1 pCi. Also, 1 millirad (1 rad) is one one-thousandth of a rad. These latter units are common levels of activity and absorbed radiation found relating to drinking water. (The Roentgen [R] is a similar unit used in describing x-ray and gamma ray exposure. The basic differences between the R and the rad centers around a unit of exposure versus a unit of energy absorption.)

TABLE D-1

ENGINEERING SHORTHAND AND GREEK PREFIXES

Greek Prefix	Abbreviation	Value	Engineering Shorthand
mega	M	1,000,000	10^6
kilo	k	1,000	10^3
centi		10	10
milli	m	$\frac{1}{1,000}$	10^{-3} one part per thousand
micro	u	$\frac{1}{1,000,000}$	10^{-6} one part per million (ppm)
nano	n	$\frac{1}{1,000,000,000}$	10^{-9} one part per billion (ppb)
pico	p	1/1,000,000,000,000	10^{-12}
femto	f	1/1,000,000,000,000,000	10^{-15}

DISCUSSION OF UNITS OF RADIOACTIVITY
(Continued)

Because of the particle mass and charge, 1 rad of alpha particles creates more biological damage than 1 rad of gamma rays. To compensate for this difference in effect a new unit was invented -- the rem, radiation equivalent man. This unit is called the dose equivalent. The dose is measured in rads and the dose equivalent is measured in rem. Frequently, the rem is called the dose. The dose equivalent is a measure of harm and is not generally an exact measurement; it is a useful unit for regulations. The rad and rem are related as follows:

number of rems (dose equivalent to man) = (Q times the number of rads (dose)

where Q is the measure of relative ability to cause biological damage in man, Q has been assigned the following values:

Q = 1	for beta particles and all electromagnetic radiations (gamma ray and x-rays)
= 10	for neutrons from spontaneous fission and protons
= 20	for alpha particles (The quality factor for alpha particles was taken to be 10 at the time regulations were promulgated for radioactivity in drinking water.)

The average human in the United States receives about 100 mrem/yr from cosmic rays (high energy protons from outside the earth) and natural background radiation. This can vary depending on where one lives and the kind of a structure in which one lives and works. The higher the altitude, the less protection afforded from the earth's atmosphere. Thus, people in Leadville, Colorado, receive 110 mrem/yr from cosmic rays, while people at sea level (i.e., Washington, DC) receive about 20 mrem/yr. Flying coast-to-coast can add as much as 5 mrem per flight.